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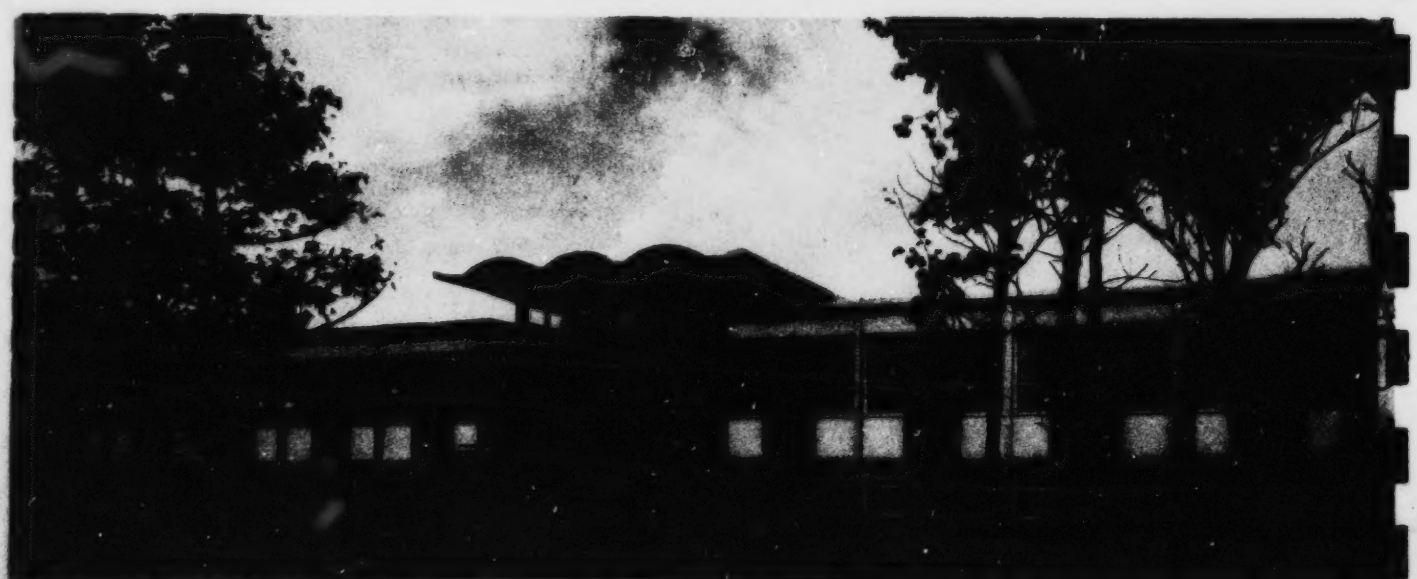

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DEMONSTRATION OF AN INTEGRATED OIL SHALE RETORT SYSTEM

FINAL REPORT

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Work on this project was conducted under the auspices of the Canada Centre for Mineral and Energy Technology, Energy, Mines and Resources Canada

DSS FILE NUMBER	15SQ.23440-3-9086
DSS CONTRACT SERIAL NUMBER	OSQ83-00127
CANMET PROJECT NUMBER	
CANMET SCIENTIFIC AUTHORITY	Dr. Edward Furimsky

MICROMEDIA

157 MP

RPC Report No. AS/85/51
DATE: December 14, 1984

Research and Productivity Council
Fuel Technology Section

SUMMARY

This is the final report for DSS Contract No. OSQ 83-00127, the requirement being the demonstration of an integrated retort system. The contract was jointly funded by the Federal Government through EMR and the Provincial Government through Provincial Holdings Limited.

The objectives of the work were to investigate three retorting techniques, namely, indirect retorting, direct retorting and an integrated system consisting of a retort and a fluidized bed combustor using Albert County oil shales and Minto coal.

The experimental program undertaken in fulfillment of the above mentioned objectives, was carried out in three main phases. These are: direct and indirect retorting experiments; co-combustion of coal/spent shale in a fluidized bed combustor and integrated system experiments. The first two phases of the test program were very successful and the results are encouraging, in the third phase however, some experimental difficulties have been encountered due to inherent limitations in the fluidized bed combustor which was not designed specifically for this project.

Some of the important findings of the study include, high oil recoveries up to 90% for indirect retorting and 81% for direct retorting, the quality of N.B. shale oil have been shown to be better than Colorado shale oils, and the spent shale was shown to be an effective sulphur capture medium.

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1.0 INTRODUCTION

The oil shale deposits of the Albert Formation in the Moncton sub-Basin, New Brunswick, are considered to be Canada's largest and highest grade oil shale reserves. The best known deposits are contained in the Albert Mines zone with oil yields averaging 20 gal/ton in the better areas. The prime deposit, at the Albert Mines zone contains an estimated 42.8 x 10^6 cubic meters (270 million barrels) in situ-shale oil reserves in an area 2.6 km^2 to a depth of 600 m (1). These reserves although appreciable are quite modest when compared to very large reserves such as the Green River Formation with an estimated recoverable oil reserve of 680 billion barrels of shale with 25 gallon/ton or higher (2).

New Brunswick's other fossil fuel resource is a high volatile bituminous coal with a high sulphur concentration in the range of 6-8%. This high sulphur content makes its utilization in conventional boilers environmentally unacceptable. Power generation is the only real consumer of N.B. coal and its continuing utilization will depend on the implementation of new technologies such as fluidized bed combustion and sorbent injection into pulverized fuel flames. Alternatively expensive SO_2 scrubbers will be required for flue gas desulfurization. The possible conversion of N.B. coal into liquid and gaseous fuel will require that the sulphur problem be solved as part of the conversion process or through additional downstream processing.

The Research and Productivity Council (RPC) in an effort to improve the economic viability of N.B. oil shale resources and to assure the continuing utilization of N.B. coal have devised and is involved in the development of a number of concepts for the co-utilization of coal and oil shale. These

processes exploit the calciferous dolomitic nature of N.B. shale which has a calcium and magnesium carbonate content in the range of 5-40% (3). In co-processes, the energy from the oil shale is recovered, either as liquid and gaseous fuels or it is utilized with that of coal for steam raising. At the same time the carbonate content of the fresh or spent shale is used to capture the sulphur species resulting from the combustion or the pyrolysis of the coal. Examples of these processes include fluidized bed co-combustion of coal and oil shale, oil shale injection into pulverized fuel flames, flue gas desulphurization using oil shale, co-pyrolysis of coal and oil shale and integration of a fluidized bed coal combustor and an oil shale retort system which is the topic of this report.

The concept of integrating a fluidized bed coal combustor and an oil shale retort system is illustrated in figure 1. In this system the heat of retorting is supplied by flue gases from a fluidized bed combustor operating on high sulphur coal, low Btu gases, spent shale and fresh shale fines. Excess heat from the combustor would be utilized for steam raising and power generation.

The concept was conceived at the Research and Productivity Council in late 1982 based on one of our earlier studies on the fluidized bed combustion of high sulphur coal and fresh shale from Albert Mines (4). The study showed oil shales are more effective, and for N.B. are a more economical alternative to limestones for capturing sulphur. Other considerations taken into account are potentially favourable impact on the economics of the retorting process. This is due to effective utilization of mined shale, through the utilization of fine particles, which according to some estimates can be up to 10% of the total weight of mined shale (5). This, together with the combustion of spent shale and the product gas can

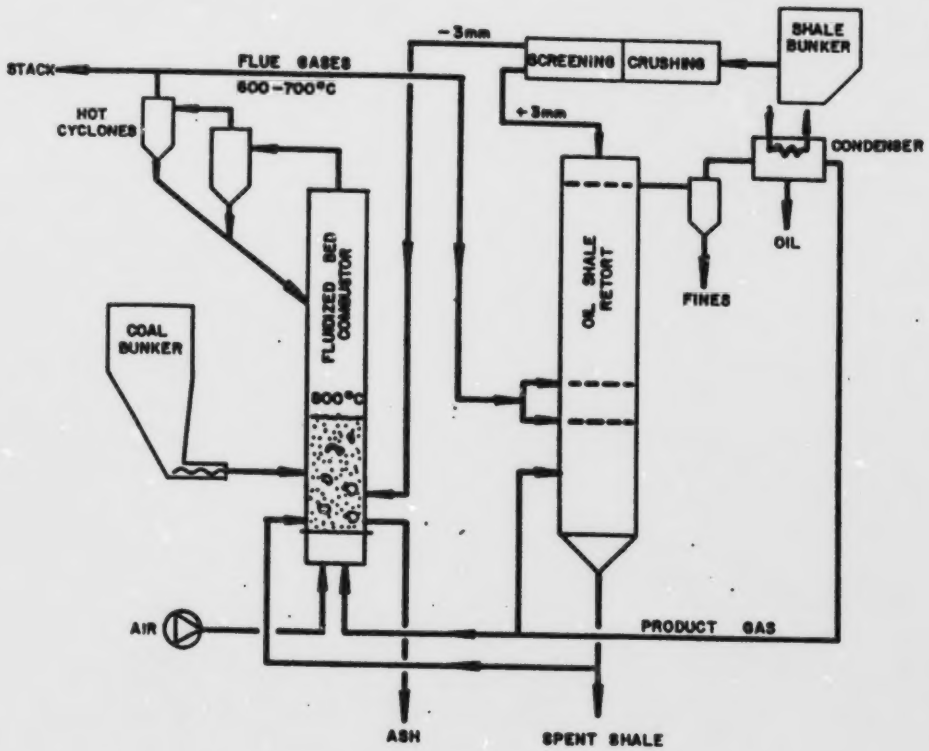


Fig. 1: Schematic of the Integrated Fluidized Bed Combustor and Oil Shale Retort System

lead to an increase in the recoverable energy from the original shale by up to 50%. The generation of steam and electricity on-site, which would eliminate power purchasing, is estimated to reduce the operating costs of the retorting process by up to 30% (5). These potential advantages, as well as local economic and environmental considerations, such as the utilization of New Brunswick high sulphur coal and the easing of the waste disposal problem of spent shale, makes this research effort a worthwhile undertaking for the Province of New Brunswick and Canada.

The experimental work for the development of the integrated system have been carried out in three phases. These are retorting studies of two feedstock obtained from the Albert Formation, fluidized bed co-combustion of Minto coal with spent shale, and integrated system experiments. This report gives details of the experimental work carried out, results, discussion and recommendations for future work.

2.0 RETORTING EXPERIMENTS

2.1 Objectives

The objectives of this phase of the work were to carry out an extensive test program, designed to gain a clear understanding of retorting characteristics of New Brunswick shales both in the indirect and direct retorting modes, as well as full characterization of product shale oil, gas and spent shale.

2.2 Experimental Set-up

A schematic of the retorting system is presented in Figure 2. It consists of a square retort, solid feeding and withdrawal equipment, product oil recovery system, and gas recycling network.

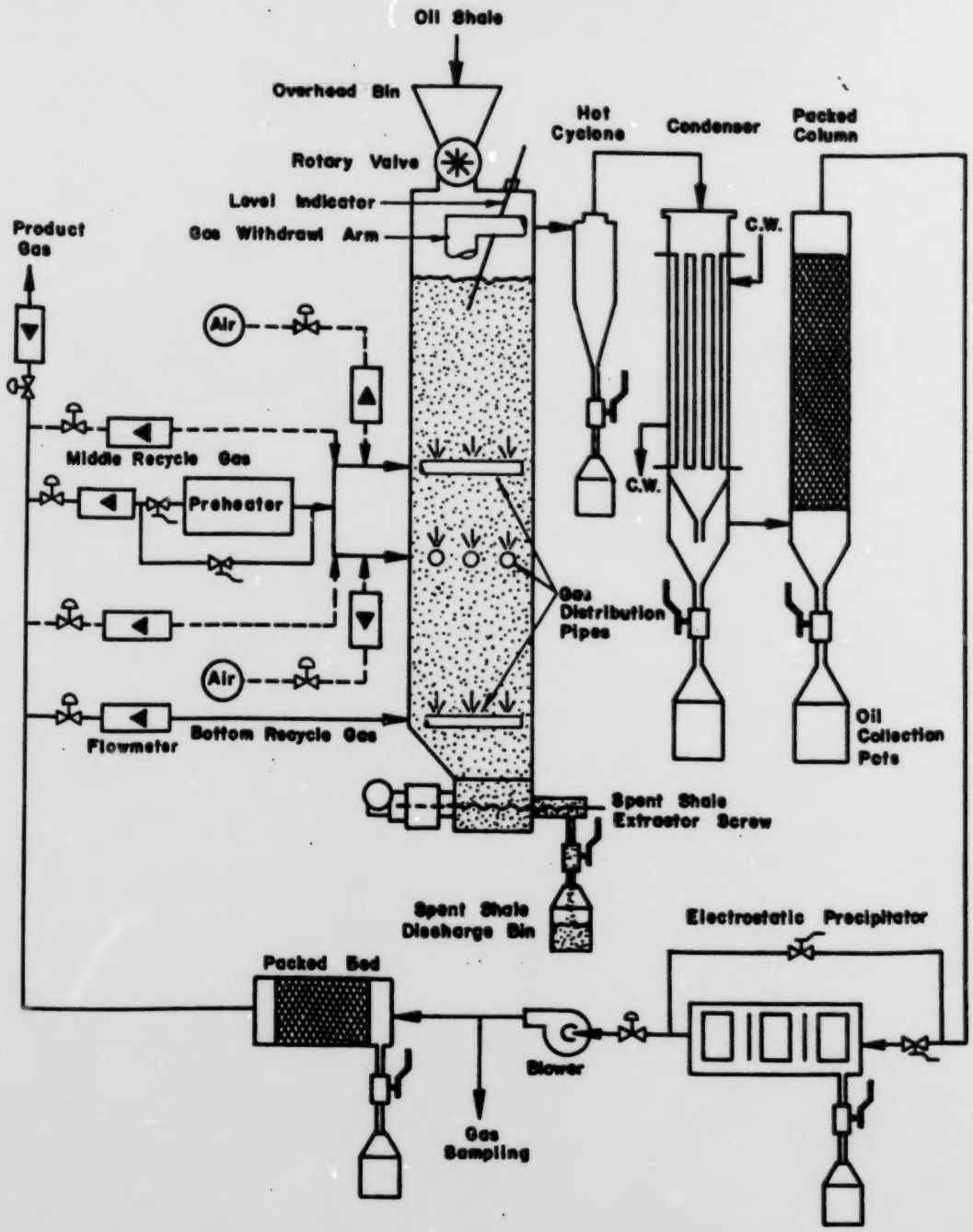


Fig. 2: Schematic of the R.P.C. Pilot Scale Oil Shale Retort System

2.2.1 The Retort

The retort has an internal square cross-sectional area of 0.053 m^2 (0.23 m x 0.23 m) and a total height of 2.4 m. The wall was constructed of three layers of material: an inner high alumina brick (selected for its good chemical, abrasive, and thermal shock resistance), a castable insulating refractory, and an external carbon steel shell. In addition, the retort was encased in a layer of insultation to minimize heat losses. A number of side doors allow access to the gas distributor pipes, thermocouple wells, and installation of an oil-fired burner for start-up.

Three levels of recycle gas feed are available. Their locations together with the positions of the thermocouples used for monitoring bed temperature are shown in Figure 3.

Gas was withdrawn near the top of the retort, through a side pipe, equipped with a baffled cup to minimize dust entrainment which can cause line plugging.

2.2.2 Solid Feeding and Withdrawal System

Oil shale was fed into the retort by gravity from an overhead hopper through a rotary valve. A predetermined amount of oil shale was loaded into the bin every hour and a timer was used to control the ON/OFF cycles of the rotary valve in order to maintain a steady supply of fresh shale. This arrangement was adopted because the minimum continuous feed rate which could be achieved using the existing rotary valve exceeds the desired feed rates.

Spent shale was discharged from a bin attached to the bottom of the retort, through a variable-speed screwfeeder into a receiving pot. The discharge rate was set so as to maintain a steady shale bed height in the retort. Bed level was measured periodically with a graduated rod inserted

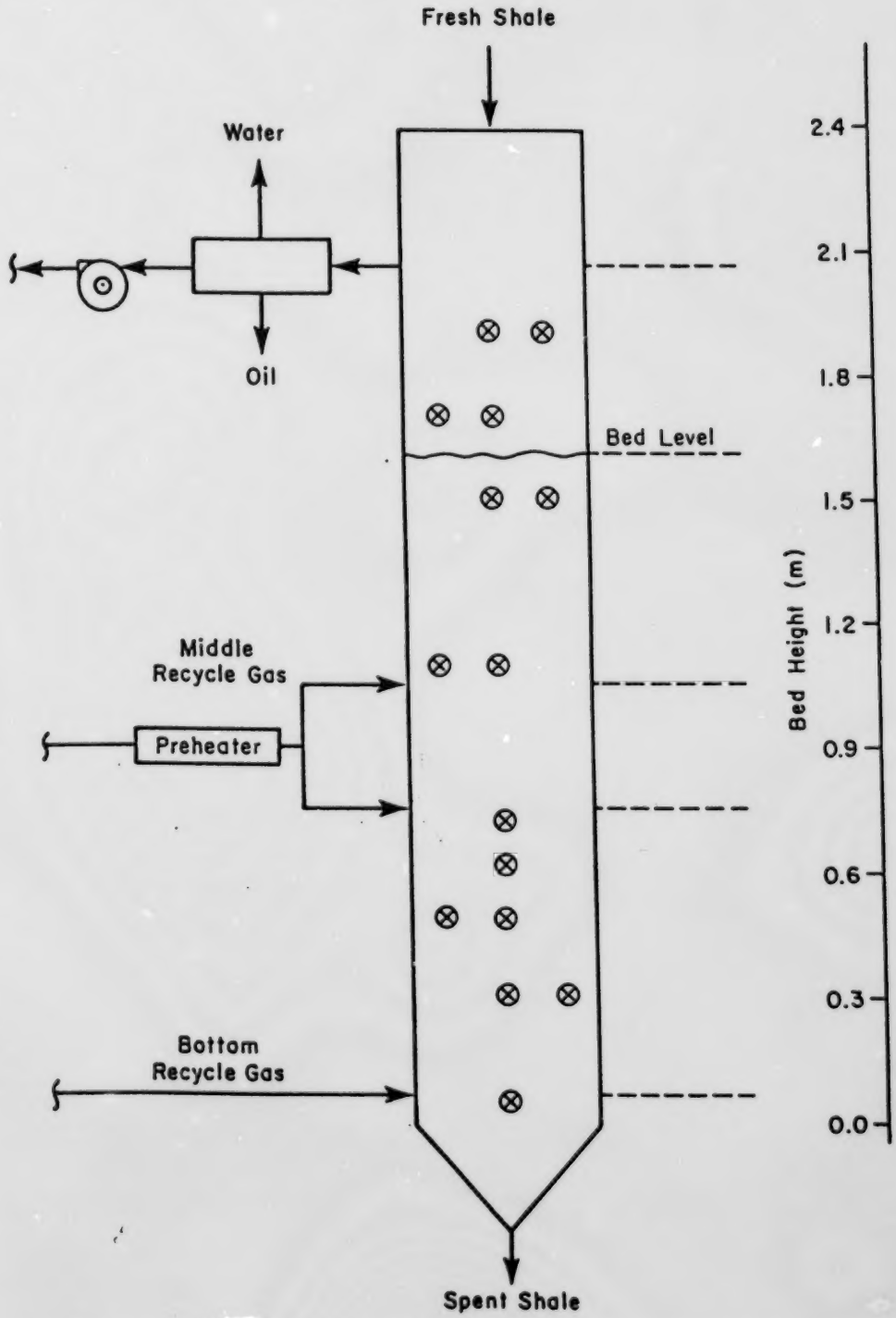


FIG. 3: SCHEMATIC OF THE RETORT SHOWING POSITIONS OF THERMOCOUPLES (⊗) AND GAS DISTRIBUTOR AND WITHDRAWL PIPES

from the top cover of the retort. It was found that this simple method was more accurate than a capacitor-type probe originally intended for this purpose, because the changing environment in the retort affects the sensitivity and calibration of the probe.

2.2.3 Product Oil Recovery System

Off-gas containing oil mist from the retort undergoes four stages of separation for product oil recovery. These are:

(a) a hot cyclone for removing heavy oils and entrained fine particles.

(b) a shell and tube heat exchanger (total heat transfer area of 0.5 m^2 with water circulating on the shell side).

(c) a packed column of rasching rings, with a column diameter of 0.36 m and an effective height of 1.55 m.

(d) an electrostatic precipitator (0.30 m wide x 1.52 m long x 0.10 m thick) with five sets of capacitor cells and ionizer. The operating voltages on the cells and ionizers are 5 KV (2 mA) and 10 KV (20 mA) respectively. It was found necessary to reheat the gas above dewpoint and to operate the electrostatic precipitator in the temperature range of 65-70^{o}C in order to prevent undesirable discharge of cell and ionizer voltages due to water condensation.

(e) A small packed column was added after the electrostatic precipitator so as to improve recovery efficiency.

2.2.4 Gas Recycling Network

Product gas from the oil recovery system was metered and recycled back to the retort, also a portion was withdrawn for gas sampling. In the indirect mode, the recycle steam was split into a bottom cold recycle to the retort and a middle recycle which was then preheated externally to the desired temperature prior to injection to the two levels of gas feed points in the retort. At each level, recycle gas was distributed among three 1.27 cm diameter SS 316 pipes imbedded in the shale and was discharged via two sets (at 90^{0} with respect to each other) of 0.16 cm holes along the side of the pipes. In the direct heating mode, air was mixed with the middle recycle and fed to the retort to substain combustion. In some experimental runs, the two levels of gas feed points were connected together and supplied from common recycle gas and air sources. In others, the flows of recycle gas and air to each level were regulated separately, so that the fuel/air mixture at each point can be adjusted as desired. Provision was also made to allow some air to be injected to the bottom recycle when necessary.

2.2.5 Gas Sampling System

On-line gas analyzers (Hydrocarbon, CO, CO_2, O_2) were used to monitor the composition of the product gas. Sample gas was continuously withdrawn from the recycle line and was conditioned via a series of filters (knock-out pot, impingers, heated by-pass filter, cloth filter, and dryers) prior to entering the analyzers. In additon, tubes of gas sample were also collected for further analysis of H_2 and N_2 content and hydrocarbon distribution using gas chromatography.

2.3 Experimental Procedure

2.3.1 Start-up

The retort can be started up, either empty or with a shallow bed of cold shale (0.3-0.4 m) in place, and a small discharge rate so as to keep the retort in motion and to avoid shale fusion. A side door above the bed was removed to fit an oil-fired burner. The burner was ignited and firing was continued for 4 hours. The brick wall becomes red hot and it retains sufficient heat which ignites the shale. During the heat up period, off-gas was vented through the stack line. Then the burner was shut off and removed. With the side door back in place, fresh oil shale was fed into the retort to fill it to the desired height. The shale was gradually heated by the hot brick to a high enough temperature to start combustion with air supplied to the bottom and middle of the retort. Off-gas was directed to the product oil recovery system (except bypassing the electrostatic precipitator until the oxygen concentration reached a safe limit which was below 3%) and recycled back to the retort. Thus, the retort was operating in the direct mode. A normal start-up takes an average of 6 to 8 hours.

2.3.2 Experimental Measurements

During the extended runs of 12 to 14 hours duration, the following measurements were made on an hourly basis:

(1) A predetermined amount of fresh shale was loaded to the overhead bin.

(2) The spent shale bin was removed and weighed.

(3) The collection pots in the product oil recovery system were emptied and their contents were separated into oil and water, and measured. It was found necessary to heat the collection pots in order to facilitate oil/water separation.

(4) The flowrates and pressure of all recycle gas streams were checked and recorded.

(5) The gas concentration in the recycle stream was recorded.

Also temperatures in the shale bed and gas streams were monitored continuously by a data-logger for further use. Two tubes of sample gas were taken per run for GC analysis.

2.4 Operating Experience

From a cold start to steady state operation, a period of 5 to 6 hours was required for stabilizing the system. In between runs, a period of 3 to 4 hours was normally required after the operating conditions were changed.

The direct mode retorting runs can commence after start-up. However, for the indirect mode experiments, switching from direct to indirect required some precautions because the oxygen level in the recycle gas must be below the flammability limit before it can be passed through the preheater. The normal procedure was to start up the preheater, cut off air supply to the middle recycle when the preheater temperature records above 200^{o}C, and to maintain a trickle of air flow to the bottom of the retort to sustain combustion. When the hot gas temperature reached the desired level, air supply to the bottom recycle was shut off.

The retort system was normally operated continuously for a period of up to 2 weeks prior to shut-down for maintenance and repair. However, operational difficulties do occur in between runs, which can interrupt the operation for a period of time. These are summarized below together with the measures taken to correct the problems as soon as possible.

(1) Clinker formation. This was particularly a problem during start-up and in the direct mode experiments. Sign of clinker formation was reflected through sudden increase in bed temperature (above 800^{o}C) and bed level

while solid discharge decreases. Thus the bed temperature must be closely monitored. A long rod was inserted into the shale bed through an opening on the cover for loosening up the shale when needed. Also, it was essential to always keep the bed in motion. A careful control and monitoring of bed temperature minimises clinker formation.

(2) Plugging of off-gas withdrawal arm and cyclone. Entrained dust and oil/water vapor often formed sludge in this part of the system blocking exit line. In this case, high pressure air must be blown back into the retort through the arm, and also into the cyclone by isolating this part of the flow line.

(3) Gas feed pipes/distributors blockage. Oil vapor escaping the recovery system was carried back to the retort by the recycle gas and may eventually become char desposit on the hot gas pipes. As a result, some of the 0.16 cm holes along the distributor pipe were plugged. This was usually reflected through increase in pressure in the line in question. There are two ways of overcoming this difficulty: (a) using high pressure air to clear the line and (b) removing the feed-through distributor pipe for cleaning. With either method, the bed temperature must be carefully monitored when idling the system. Also, in order to minimize the source of problem, several knock-out pots are installed along the recycle line for trapping condensables.

(4) Solid withdrawal. Spent shale from the retort tended to generate large amount of fines when passing through the auger of the screwfeeder. These fines accumulated and eventually blocked the auger, interrupting solid discharge. To prevent this, a vibrator was attached to the screwfeeder discharge arm.

(5) Low recovery efficiency in the electrostatic precipitator. The source of the problem was traced to undesirable discharge of cells and ionizer voltages across the gap between the insulator terminals and the precipitator casing. As a result a slight modification in the design was made to adapt the unit to this application.

2.5 Raw Materials

2.5.1 Shale Acquisition

Two bulk oil shale samples were obtained from Albert Mines zone. These were taken from two test trenches* about 300 m apart. The geographical location of the trenches and pertinent geological and other information are given in Appendix A.

2.5.2 Shale Preparation and Characterization

As-received shale contained a very high proportion of moisture and as such, could not be screened. So the shale was dried before screening. The drying was carried out at 80°C for 48 hours. It has been reported in the literature that drying under those conditions will not adversely affect the oil yield (6). The dried shale was then screened to take off particle size less than 3.175 mm (1/8 inch) and greater than 12.7 mm (½ inch). Detailed size analysis of (-½ to 1/8") fraction for both the shales are shown in Table 1.

TABLE 1
Oil Shale Particle Size Analysis

Screen Size, mm (inch)	Shale 1 wt (%)	Shale 2 wt (%)
- 12.7 + 9.52 (-0.500 + 0.375)	28.74	26.84
- 9.52 + 8.0 (-0.375 + 0.312)	13.68	11.48
- 8.0 + 4.0 (-0.312 + 0.157)	44.00	47.74
- 4.0 + 3.36 (-0.157 + 0.132)	4.28	5.46
- 3.36 + 2.83 (-0.132 + 0.111)	3.65	4.99
- 2.83 fines (-0.111 fines)	5.65	3.49

* Shale from Trench 1 was designated as shale 1 and that from Trench 2 as shale 2.

About 86% of the shales falls within the size range of 4 to 12.7 mm. Average particle sizes are 7.38 mm and 7.25 mm for shale 1 and shale 2 respectively. Detailed chemical analyses and Fischer assay on the representative samples of both shales are shown in Table 2. It can be seen that there are considerable differences in chemical compositions and Fischer assay yields between these two shales. Shale 1 can be regarded as a better quality shale than shale 2 based on these analyses.

TABLE 2
Chemical Analyses of Oil Shales

	Shale 1	Shale 2
Proximate Analysis (wt%)		
Moisture	0.68	0.43
Ash	77.55	83.16
Volatile matter	21.77	16.41
Ultimate Analysis (wt%)		
Carbon - organic	11.40	9.95
inorganic	3.36	1.98
Hydrogen	1.86	1.48
Nitrogen	0.10	0.30
Oxygen	4.96	2.50
Sulphur	0.77	0.63
Ash	77.55	83.16
Ash Analysis (wt%)		
SiO_2	57.82	63.71
Al_2O_3	15.62	17.14
Fe_2O_3	7.86	4.45
CaO	10.18	5.70
MgO	4.09	2.94
Na_2O	2.11	3.88
K_2O	2.32	2.18
Fischer Assay (wt%)		
Oil yield	7.76	5.91
H_2O yield	1.80	1.70
Gas lost	1.14	2.39
Oil yield (Imp Gal/ton)	21.0	15.5
Density (g/cc at 15.5°C)	0.7391	0.7592
Gross Heat of Combustion (Btu/lb)	2005	1700

2.6 Experimental and Calculated Results

Forty-nine runs in total were carried out, excluding the short duration runs, thirty-one were considered successful and evaluated accordingly. The first ten were trial runs which were made for preliminary assessment of the effects of all the independent variables and for providing hands-on experience for all the personnel involved, see Appendix C. The first ten runs were marked by a low oil recovery of about 40%. It was established during these runs that bed height has a significant effect on the oil recovery. Details of effect of bed height will be discussed later.

All the successful runs are grouped into four sets based on shale quality and retorting mode. These are shown in Table 3.

Table 3

Grouping of the Successful Runs

	Shale No.	Retorting Mode	Run No.
Set 1	1	Indirect	11-17, 21-23
Set 2	2	Indirect	27-35
Set 3	1	Direct	18, 20, 36, 37, 46-49
Set 4	2	Direct	41, 42, 43, 44, 45

Other missing runs such as run no. 25, 26, etc. which were not regarded as successful runs, were aborted prematurely because of their lower than expected yields. Also a considerable number of short duration runs were carried out in order to explore and improve the oil recovery. The successful runs were a direct result of these short duration runs.

Compilation and processing of raw retorting data were carried out using a computer program specially developed for this purpose. Figs. 4 and 5 are examples of the computer outputs for direct and indirect retorting, respectively. Output for other runs are given in the Appendix D. The output consists of operating conditions, overall mass balance, product gas analyses with calculated heating values, distribution of organic carbon and energy among the products. Overall mass balance was carried out on the basis of 100 kg of fresh shale feed to the retort. Mass balance for most of the runs can be closed within 5%, however, in extreme cases this ranged from -12 to +11%. With one exception, indirect retorting mass balances showed higher output than input, this was due to the infusion of air into the retort primarily through the rotary valve, due to negative retort pressure, generated by the recycle gas blower. In direct retorting, the introduction of compressed air to the retort tended to lessen this effect resulting in reduced or no air leakage.

The gas analyses shown in Figs. 4 and 5 were based on on-line analyzers and GC analysis of batch samples. On-line analyzers continuously recorded oxygen, carbon dioxide, carbon monoxide and hydrocarbon. GC analysis produced complete analysis of the product gas, however, it was found that there was a discrepency between these two sets of analyses due to contamination of the batch samples, particularly after a prolonged storage. The results from the continuous gas analyzers were found to be quite reliable and accurate. Therefore, only nitrogen, hydrogen and the distribution of hydrocarbon readings were taken from GC analysis and adjusted with the other readings from on-line gas analyzers to produce complete gas analysis. The heating value of the gas was then calculated from the respective heating values of the component gases.

Also shown in Figs. 4 and 5 are the energy recovery and oil yield. Energy recovery which can be regarded as retorting efficiency was calculated based on the ratio of energy recovered in the form of oil and gas to that present in the original shale. In indirect retorting heat input to the recylce gas preheater was taken into account. Percent oil yield has been defined as the fraction of the oil recovered during a run relative to that of Fischer assay yield.

All the essential information shown in Figs. 4 and 5 are summarized for each run of all four sets of experiments and are shown in Tables 4 to 7. As can be seen from the tables, all the process variables have been investigated to assess their effects on the oil yield. Details of the effect of these parameters will be discussed later.

Bed temperature along the retort height was continuously monitored by a trend chart recorder and recorded by a data logger. Temperature profile was drawn from those readings by taking the average of all the readings for each thermocouple. It can be seen from Fig. 3 that two thermocouples were placed at the same bed height, but at different locations of bed cross section. Averge of the two readings were assigned to that bed height. Two temperature profiles together with summary of mass balance for both direct and indirect retorting modes are shown in Figs. 6 and 7. All other temperature profiles are shown in Appendix D along with the computer outputs.

Spent shale from all the runs were analyzed for organic and inorganic carbon so that organic carbon balance could be carried out. Detail results are shown in Table 8. Four spent samples representing both retorting modes and shale quality were further analyzed to produce heating values and ultimate analysis. These selected spent shales represent the highest and

```
EXPERIMENT NO:13                SHALE NO: 1

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M:     1.53
FEED RATE, KG/HR:    20.00
DURATION, HR:    13.00
RESIDENCE TIME IN HR:     4.05
RATIO OF RECYCLE GAS TO SHALE, KG/KG:     1.87
RECYCLE GAS SPLIT, %: BOTTOM:     38.0 MIDDLE:     62.0

INPUT IN KG

FRESH SHALE:   100.00
ACCUM/DEPLE:     5.05
TOTAL INPUT:   105.05

OUTPUT IN KG

SPENT SHALE:    92.25
EXHAUST GAS:     0.
ANALYZER INTAKE:     8.26
OIL PRODUCED:     7.71
WATER FORMED:     3.13
TOTAL OUTPUT:   111.36
% UNACCOUNTED:    -6.00

BOTTOM RECYCLE GAS, KG:    71.81
MIDDLE RECYCLE GAS, KG:   116.14

GAS ANALYSIS IN MOL %

H2:     4.30
N2:    79.35
O2:     1.30
CO2:     6.00
CO:     4.16
CH4:     1.11
C2:     1.70
C3:    2.030
C4:    0.050

BTU PER SCFM:   125.81

DISTRIBUTION OF ORGANIC CARBON
% OIL    55.38
% SPENT SHALE:    37.90
% GAS:     5.72

% UNACCOUNTED CARBON:     1.00

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL:    57.92
GAS:     5.39
SPENT SHALE:    20.41

YIELD, % OF F.A:    88.60
```

Fig. 4: Computer Output Listing Experimental Conditions and Results for an Indirect Retorting Experiment

```
EXPERIMENT NO:48                    SHALE NO: 1

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M:     1.46
FEED RATE, KG/HR:    20.00
DURATION, HR:    10.00
RESIDENCE TIME IN HR:     3.86
RATIO OF RECYCLE GAS TO SHALE, KG/KG:     2.12
RECYCLE GAS SPLIT, % : BOTTOM:     88.3 MIDDLE:     11.7

INPUT IN KG

FRESH SHALE:   100.00
AIR MIDDLE:    27.62
AIR BOTTOM:     0.
ACCUM/DEPLE:     4.38
TOTAL INPUT:   132.00

OUTPUT IN KG

SPENT SHALE:    80.20
EXHAUST GAS:    27.07
ANALYZER INTAKE:     7.75
OIL PRODUCED:     6.27
WATER FORMED:     3.67
TOTAL OUTPUT:   124.96
% UNACCOUNTED:     5.33


MID AIR SPLIT
MID AIR UPPER, KG:    12.51
MID AIR LOWER, KG:    15.11

BOTTOM RECYCLE GAS, KG:   186.76
MIDDLE RECYCLE GAS, KG:    24.86

MIDDLE RECYCLE GAS SPLIT, KG
UPPER, KG:    12.97
LOWER, KG:    11.88

GAS ANALYSIS IN MOL %

H2:     2.00
N2:    78.36
O2:     0.34
CO2:    14.20
CO:     1.97
CH4:     1.10
C2:     0.73
C3:    0.400
C4:    0.300

BTU PER SCFM:    58.96


DISTRIBUTION OF CARBON
% OIL    45.35
% SPENT SHALE:    33.36
% GAS:    14.36
% UNACCOUNTED CARBON:     6.93


ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL:    56.28
GAS:    11.82
SPENT SHALE:    21.08


YIELD, % OF F.A:    71.40
```

Fig. 5: Computer Output Listing Experimental Conditions and Results for a Direct Retorting Experiment

TABLE 4

Set 1

Summary of Experimental Conditions and Results
Mode: Indirect, Shale: 1, Fischer Assay: 21.0 Gal/ton

Run No.	Feed Rate Kg/hr	Average Bed Height m	Shale Residence Time hr	Total Recycle Gas Kg/100 kg of shale	Recycle Gas Split, kg/100 kg of shale		Retorting Recovery % of Fischer Assay	Energy Distribution % of Fresh Shale	
					Middle	Bottom		Oil	Gas
11	20	1.64	4.34	164	153.8	10.6	72.6	50.40	4.42
13	20	1.53	4.05	187	116.1	71.3	88.6	57.92	5.39
15	20	1.48	3.91	182	90.5	91.4	69.03	47.95	4.67
22	20	1.43	3.78	201	124.8	76.4	74.9	52.39	4.82
16	16	1.36	4.50	173	103.1	69.8	63.3	42.63	5.16
17	16	1.43	4.73	214	137.9	76.1	72.8	51.13	5.11
21	16	1.48	4.89	286	176.8	109.4	78.5	54.26	4.80
12	25	1.63	3.45	133	16.5	16.5	65.2	48.77	5.03
14	25	1.49	3.15	147	92.2	55.2	65.3	49.1	4.10
23	25	1.49	3.15	178	112.7	65.2	67.5	46.99	3.96

TABLE 5

Set 2

Summary of Experimental Conditions and Results
Mode: Indirect, Shale: 2, Fischer Assay: 15.5 Gal/Ton

Run No.	Feed Rate Kg/hr	Average Bed Height m	Shale Residence Time hr	Total Recycle Gas kg/100 kg of shale	Recycle Gas Split, Kg/100 kg of shale		Retorting Recovery % of Fischer Assay	Energy Distribution % of Fresh Shale	
					Middle	Bottom		Oil	Gas
27	20	1.41	3.73	211	132.4	78.6	89.3	55.79	5.95
28	20	1.53	4.05	197	120.7	76.1	70.2	46.22	5.35
29	20	1.60	4.22	243	151.3	91.5	84.9	54.37	4.58
35	20	1.62	4.28	247	161.0	86.2	84.3	55.0	3.38
32	16	1.62	5.36	257	161.0	95.7	72.5	42.4	4.30
34	16	1.57	5.19	293	185.0	107.6	67.7	38.24	4.87
30	25	1.61	3.41	215	157.0	58.4	78.5	45.63	3.58
31	25	1.58	3.34	224	153.7	70.0	72.7	42.50	3.01

TABLE 6

Set 3

Summary of Experimental Conditions and Results
Mode: Direct, Shale: 1, Fischer Assay: 21.0 Gal/ton

Run No.	Feed Rate kg/hr	Average Bed Height m	Shale Residence Time hr	Total Air kg/100 kg of shale	Air Split wt% Middle	Air Split wt% Bottom	Total Recycle Gas kg/100 kg of shale	Recycle Gas Split, wt% Middle	Recycle Gas Split, wt% Bottom	Retorting Recovery % Fischer Assay	Energy Distribution % Fresh Oil	Energy Distribution % Shale Gas
18	20	1.43	3.78	31.4	100	0.0	117	55	45	60.4	49.64	11.0
20	25	1.51	3.20	28.74	100	0.0	144	12	88	75.1	63.4	8.7
36	20	1.55	4.10	28.44	77	23.0	153	19	81	61.6	40.20	21.4
37	20	1.52	4.02	35.7	74	26.0	148	26	74	63.6	40.2	10.5
46	20	1.74	4.60	32.84	100	0.0	170	23	77	77.3	60.1	12.3
47	20	1.55	4.10	30.89	100	0.0	213	16	84	81.4	64.4	10.3
48	20	1.46	3.86	27.62	100	0.0	212	12	88	71.4	56.3	11.8
49	20	1.61	4.26	39.32	100	0.0	218	21	79	61.8	50.1	14.5

TABLE 7

Set 4

Summary of Experimental Conditions and Results
Mode: Direct, Shale: 2, Fischer Assay: 15.5 Gal/ton

Run No.	Feed Rate kg/hr	Average Bed Height m	Shale Residence Time hr	Total Air kg/100 kg of shale	Air Split wt% Middle	Air Split wt% Bottom	Total Recycle Gas kg/100 kg of shale	Recycle Gas Split, wt% Middle	Recycle Gas Split, wt% Bottom	Retorting Recovery % Fischer Assay	Energy Distribution % Fresh Oil	Energy Distribution % Shale Gas
41	20	1.74	4.60	30.64	100	0	217	14	86	63.9	46.63	11.60
42	20	1.74	4.60	30.59	100	0	189	16	84	59.3	43.9	12.33
43	20	1.74	4.60	30.11	100	0	164	19	81	58.5	44.08	11.33
44	20	1.58	4.18	29.07	100	0	171	20	80	71.1	58.97	17.45
45	20	1.69	4.47	39.94	100	0	176	24	76	65.3	49.26	14.43

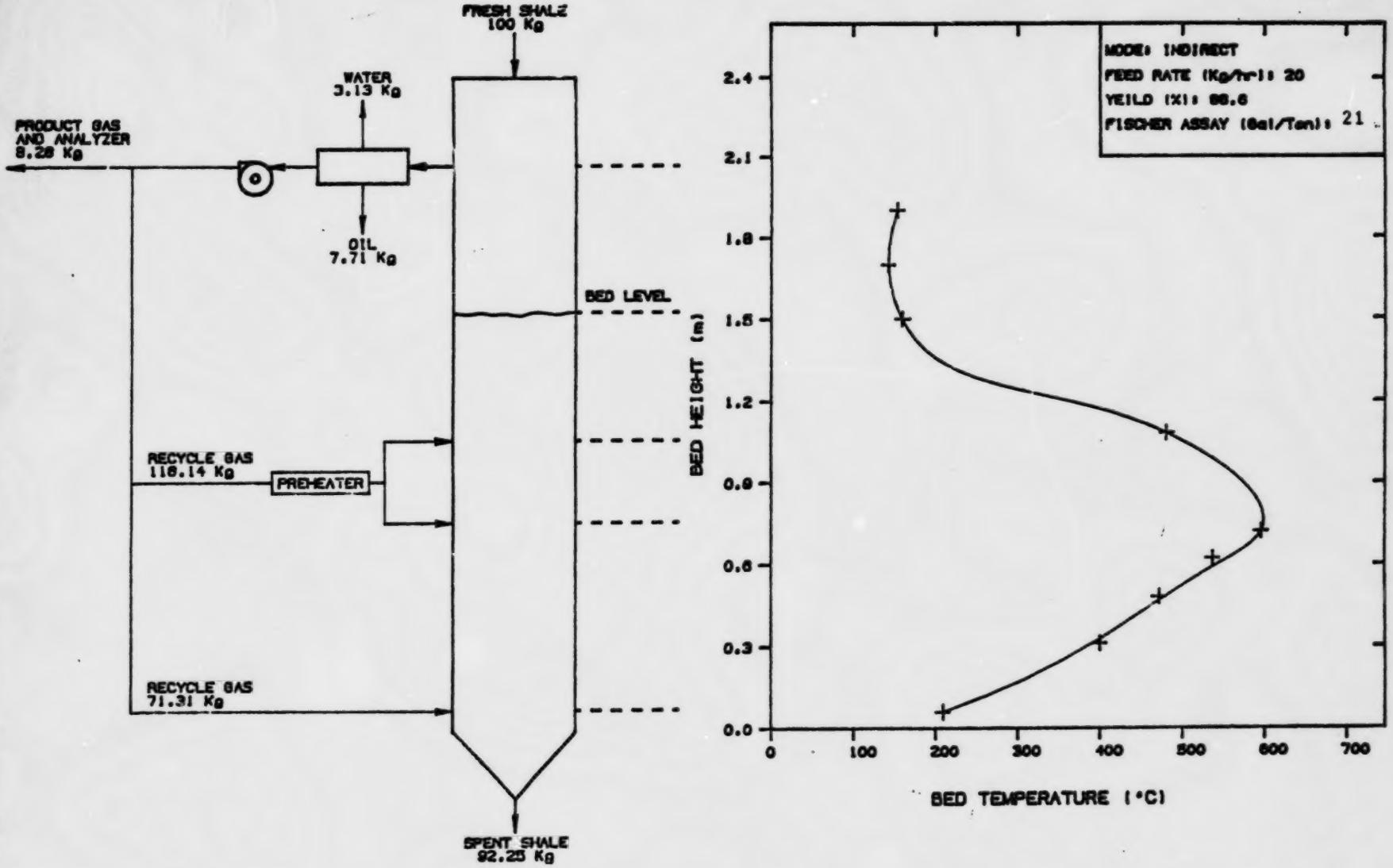


FIG 6 : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 13

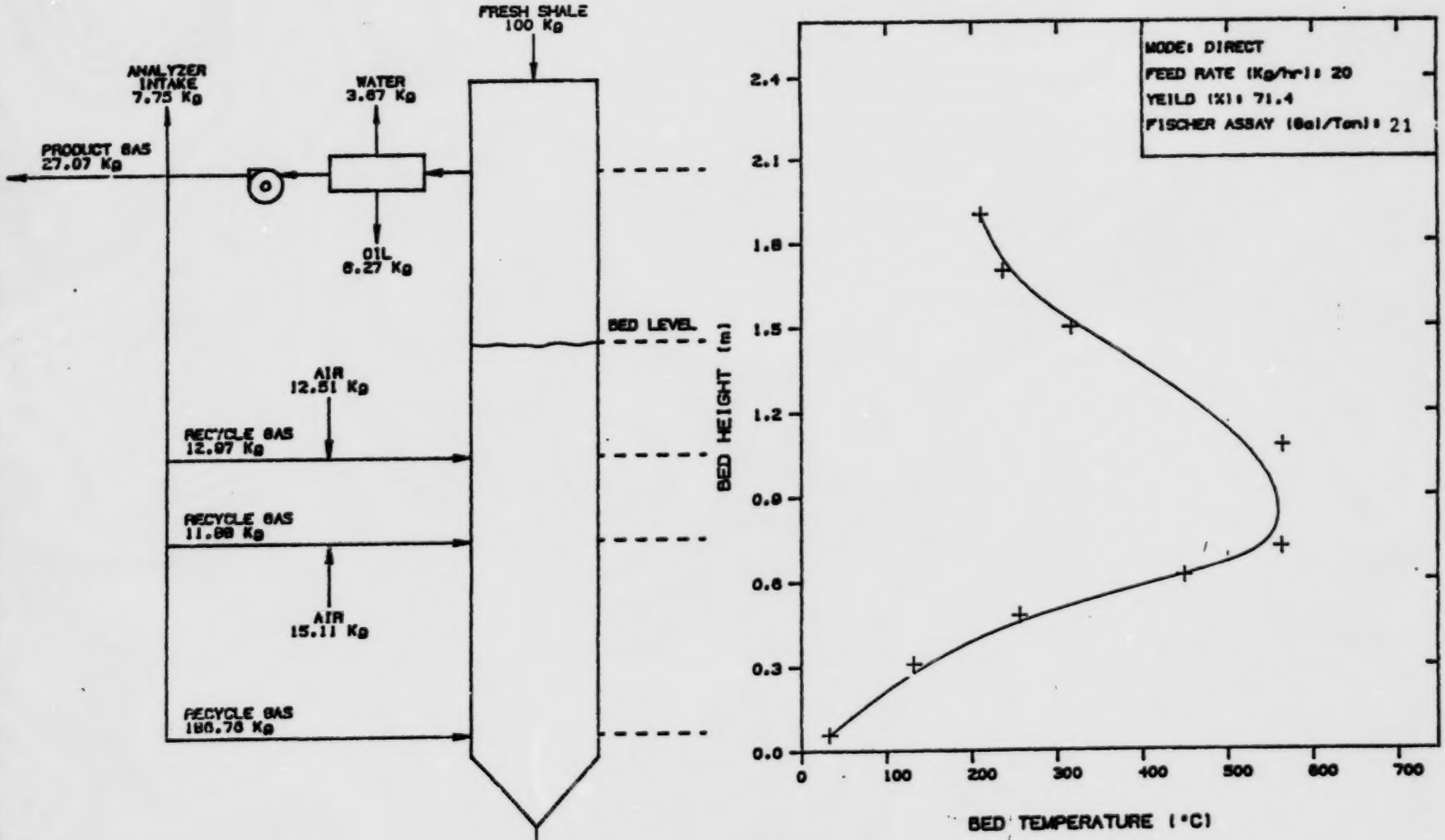


FIG 7: OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 48

TABLE 8

Organic and Inorganic Carbon of Spent Shale and Heating Values of Eight Samples

Run No.	Organic Carbon Wt%	Inorganic Carbon Wt%	Heating Values Btu/lb
11	4.62	2.52	--
12	5.22	2.00	--
13	4.92	2.46	726
14	3.71	3.90	--
15	5.36	1.77	--
16	5.58	4.01	999
17	4.66	2.96	--
18	5.87	0.84	--
20	5.21	2.10	--
21	4.58	2.32	--
22	5.03	2.10	--
23	4.96	2.86	--
27	4.28	1.76	600
28	4.02	1.19	--
29	3.96	0.73	--
30	3.27	2.10	--
31	3.62	2.28	--
32	3.86	1.03	--
33	3.90	1.08	--
34	3.81	2.09	525
35	4.08	1.41	--
36	4.25	0.48	537
37	4.68	0.54	--
41	4.18	0.62	--
42	3.28	1.39	--
43	3.62	1.14	490
44	3.20	1.34	510
45	3.36	0.89	--
46	4.60	1.84	--
47	3.59	2.45	467
48	4.95	1.38	--
49	3.72	2.49	--

the lowest oil recovery in each retorting mode, the analytical results are shown in Table 9.

Oil, separated from the product gas in five different stages, were collected in separate containers during the experimental run. Total volume of oil collected depended on the duration of the run and the oil recovery, it ranged from 15 litre to 30 litres. Composite sample of about 2 litres were made, by mixing the product oils in proportion to the amounts collected in each oil/gas separating devices (condenser, column, etc.). The composite samples representing each run were analyzed for density, carbon, hydrogen, nitrogen, sulfur, flash point, pour point and heating values. Oxygen was determined by difference. Analytical results for each set of experimental runs are shown in Tables 10 to 13.

TABLE 9

Chemical Analyses of Spent shale

	Mode: Indirect		Mode: Direct	
	Shale 1 Run 16	Shale 2 Run 27	Shale 1 Run 47	Shale 2 Run 43
Ultimate Analysis, ot%				
Carbon - organic	4.81	4.28	4.31	3.62
inorganic	2.41	1.76	1.73	1.14
Hydrogen	0.82	0.48	0.40	0.31
Nitrogen	0.38	0.21	0.24	0.23
Sulfur	0.75	0.45	0.67	0.59
Oxygen (by Difference)	7.13	2.52	4.95	0.81
Ash	83.7	90.3	87.7	93.3
Heating Values (Btu/lb)	999	600	467	490
Oil Yield, %	63.3	89.3	81.4	58.5

TABLE 10

Set 1

Properties of Shale Oil
Mode: Indirect, Shale: 1, Fischer Assay: 21.0 Gal/Ton

Run No.	API Gravity	Elemental Analysis wt% C	H	N	S	O (by Diff)	H/C Ratio	Pour Point °F	Flash Point °F	Kinematic Viscosity Cst @ 122°F	Heating Value Btu/lb	% Recovery
11	30.4	86.26	12.16	0.65	0.47	0.46	1.69	70	139	5.73	18776	72.6
12	31.1	86.16	12.17	0.80	0.51	0.36	1.69	70	134	5.44	18943	65.2
13	28.7	86.51	11.95	0.79	0.47	0.28	1.66	75	142	8.44	18504	88.6
14	30.2	86.23	12.28	0.80	0.48	0.21	1.70	70	135	6.75	18549	65.3
15	29.8	86.41	12.19	0.82	0.46	0.12	1.69	75	139	7.47	18619	69.0
16	30.0 (26.8)	85.46 (85.0	12.07 11.4	0.68 0.70	0.52 0.52	1.27 2.4)	1.69	70	153	8.88	18701	63.3
17	29.5	86.09	11.92	0.96	0.52	0.51	1.66	75	153	8.79	18632	72.8
21	27.8	86.12	12.01	0.94	0.55	0.38	1.67	70	158	10.17	18512	78.5
22	27.5	86.03	11.87	0.97	0.53	0.60	1.66	75	162	11.37	18490	74.9
23	29.5	86.02	12.02	0.92	0.54	0.50	1.68	75	146	8.14	18592	67.5

TABLE 11

Set 2

Properties of Shale Oil
Mode: Indirect, Shale: 2, Fischer Assay: 15.5 Gal/ton

Run No.	API Gravity	Elemental Analysis wt% C	H	N	S	O (by Diff)	H/C Ratio	Pour Point °F	Flash Point °F	Kinematic Viscosity Cst @ 122°F	Heating value Btu/lb	% Recovery
27	21.8	86.46	11.80	1.16	0.28	0.30	1.64	60	166	13.40	18302	89.3
28	25.2	86.29	11.78	1.28	0.30	0.35	1.64	60	152	16.75	18461	70.2
29	22.6	86.38	11.62	1.37	0.29	0.34	1.61	60	160	17.32	17379	84.9
30	23.1	86.22	11.61	1.35	0.26	0.56	1.62	55	179	18.42	17541	72.7
31	23.3	86.55	11.39	1.07	0.30	0.69	1.58	55	182	17.59	17651	72.7
32	25.0	85.42	11.11	1.29	0.28	1.90	1.56	60	174	19.25	17929	72.5
34	26.2	86.26	11.38	1.35	0.26	0.75	1.58	55	129	11.59	18263	67.7
35	25.0	86.36	11.08	1.24	0.25	1.07	1.54	55	132	10.79	18384	84.3

TABLE 12

Set 3

Properties of Shale Oil
Mode: Direct, Shale: 1, Fischer Assay: 21.0 Gal/Ton

Run No.	API Gravity	Elemental Analysis wt% C	H	N	S	O (by Diff)	H/C Ratio	Pour Point °F	Flash Point °F	Kinematic Viscosity Cst @ 122°F	Heating Value Btu/lb	% Recovery
36	25.9	86.04	11.04	1.18	0.25	1.49	1.54	60	182	12.80	18393	61.6
	(25.2)	(85.5	11.70	1.0	0.50	1.30)						
37	27.1	85.51	11.3	1.04	0.25	1.40	1.59	60	164	10.93	18563	63.6
46	29.5	85.96	11.55	0.79	0.49	1.21	1.61	70	158	8.14	18569	77.3
47	28.0	86.19	11.81	0.83	0.54	0.63	1.64	75	174	11.61	18770	81.4
	(23.5)	(85.7	11.3	0.90	0.24	1.8)						
48	28.2	86.38	11.27	0.84	0.54	0.97	1.57	70	176	10.34	18772	71.4
49	29.3	86.51	11.62	0.80	0.48	0.59	1.61	70	178	8.06	18833	61.8

TABLE 13

Set 4

Properties of Shale Oil
Mode: Direct, Shale: 2, Fischer Assay: 15.5 Gal/Ton

Run No.	API Gravity	Elemental Analysis wt% C	H	N	S	O (by Diff)	H/C Ratio	Pour Point °F	Flash Point °F	Kinematic Viscosity Cst @ 122°F	Heating Value Btu/lb	% Recovery
41	27.5	86.11	11.31	1.25	0.25	1.08	1.58	60	178	12.82	18523	63.9
42	25.7	85.41	11.33	1.14	0.24	1.88	1.59	60	178	15.80	18370	59.3
43	25.9	86.61	11.04	1.23	0.23	0.89	1.53	55	174	12.92	18485	58.5
44	25.5	86.18	11.56	1.28	0.22	0.76	1.61	55	170	14.10	18536	71.1
45	25.2	86.09	11.06	1.29	0.25	1.31	1.54	60	172	14.23	18565	65.3

2.7 Discussion

The experimental program was aimed at identifying the effect and significance of the various operating parameters in determining oil and gas yields, and whether the two shales tested exhibit different retorting characteristics. The operating parameters together with their range of values investigated are given in Table 14.

TABLE 14
Range of Operating Conditions

Parameters		Range Tested	
		Indirect Retorting	Direct Retorting
Shale feed rate	kg/hr	16 - 25	16 - 25
Bed height	m	1.36 - 2.3	1.43 - 2.3
Recycle gas/shale ratio	kg/kg	1.3 - 2.9	1.2 - 2.2
Recycle gas* distribution	%	49.7 - 93.5	11.5 - 45.1
Recycle gas temeprature	^{o}C	600 - 660	25
Air/shale ratio	kg/kg	--	0.28 - 0.40
Air distribution*	%	--	74 - 100

* percent to the middle recycle stream

The effect of each of these operating parameters, on oil yield, carbon conversion, process performance and quality of products are discussed below.

2.7.1 Effect of the Operating Parameters

2.7.1.1 Effect of Bed Height

As mentioned earlier, the first ten trial runs were carried at using a deep bed and these runs were marked by a low oil recovery. The

operating conditions for some of these early runs are given in Table 15, also given are the operating conditions for run 17. As can be seen from the table the operating conditions for run 17 are very similar to those for runs 7 and 8, except for bed height. Lowering the bed height from 2.25 to 1.43 m, the oil recovery increased substantially from 28.4% to 72.8%. This could be due to differences in the heat-up rate for the two sets of experiments. For the early experiments, the relatively deep heat-up zone gave rise to slow and gradual increase in shale particles temperature i.e. a slow heat-up rate, and vice versa. Another possible explanation is that in the case of a deep bed, the oil generated in the retorting zone could be trapped by the cold shale particles in the relatively deep preheating zone.

2.7.1.2 Effect of Bed Temperature Profile

Three indirect mode temperature profiles for shale 1 representing the highest, the lowest and a medium oil recovery are shown in Fig. 8. For shale 2, the corresponding profiles are given in Fig. 9. The bell shape of the curves are common with all recorded temperature profiles, see Appendix D. The maximum temperature for most of the indirect retorting runs did not exceed 620^{o}C. As expected, the highest temperature was recorded approximately at the same bed height as the inlet of the preheated recycle gas.

Most oil generation takes place in the retorting zone which starts at a bed height corresponding to a temperature of approximately 300^{o}C, which is considered as the lowest temperature at which N.B. shale start to lose weight (7). Temperature profile in this zone significantly affected the oil recovery. It appears that a critical temperature profile in this zone is required for maximum oil recovery, deviation from such profile

TABLE 15

Effect of Bed Height on Oil Recovery

Shale 1
Mode: Indirect

Run No.	Mode	Feed Rate kg/hr	Average Bed Height m	Shale Residence Time hr	Total Recycle Gas kg/100 kg of shale	Total Gas Distribution* % to the middle	Oil Recovery %
7	Indirect	16.0	2.25	7.43	223.0	53.0	28.4
8	Indirect	16.0	2.23	7.37	218.0	87.0	41.8
9	Indirect	16.0	2.27	5.00	152.0	91.0	42.9
17	Indirect	16.0	1.43	4.73	214.0	64.0	72.8

* Remainder of the recycle gas was fed to the bottom of the retort.

resulted in a low oil recovery. For Shale 1, Figure 8 shows a correspondence between peak temperature and oil recovery, while for shale two shown in figure 9, the highest oil recovery coincides with the lowest peak temperature. However it is notable that the temperature profiles in the retorting zone for runs 13 and 27 (highest oil recovery for both shales), are quite similar. This suggests that there is an optimum retorting zone temperature profile. Deviation from this optimum to a higher temperature could promote secondary cracking and lower temperatures would not be adequate to pyrolyze the shale sufficiently.

Figure 10 shows direct mode temperature profiles for highest and lowest oil recoveries. Unlike indirect mode, the general shape of the temperature profiles were not similar for all the runs. Run 47 which registered the highest oil recovery was marked by a broad high temperature zone, in contrast, run 49 with the lowest oil recovery showed a sharp peak followed by gradual decline in temperatures. Also, there is a considerable difference in temperature in the upper part of the bed. It is worthwhile noting that, these two runs have essentially identical experimental conditions except for air feed rate which led the variation in the temperature profiles.

The temperature in the cooling zone which extended from bed height zero to the combustion zone depends on the amount of bottom recycle. The temperature of the discharge shale could therefore, be effectively controlled by the amount of gas recycled to the bottom of the retort.

2.7.1.3 Effect of Shale Residence Time

Shale overall residence time does not exhibit a direct correlation with the oil yield, however, residence times within a certain temperature zones appears to play a role in determining oil yield. In order to identify

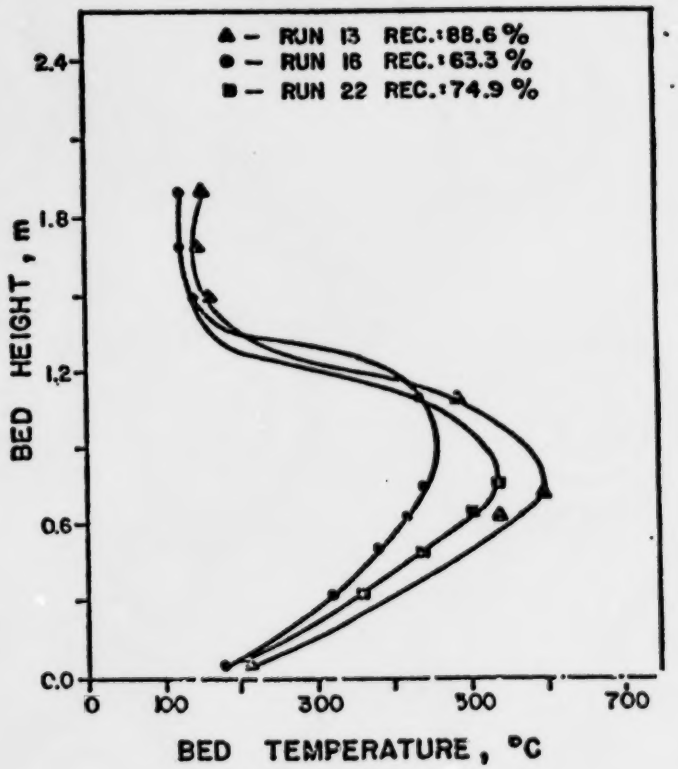


Fig. 8: Retort Temperature Profile for the Highest, the Lowest and an Intermediate Oil Recovery Indirect Retorting Runs Using Shale 1

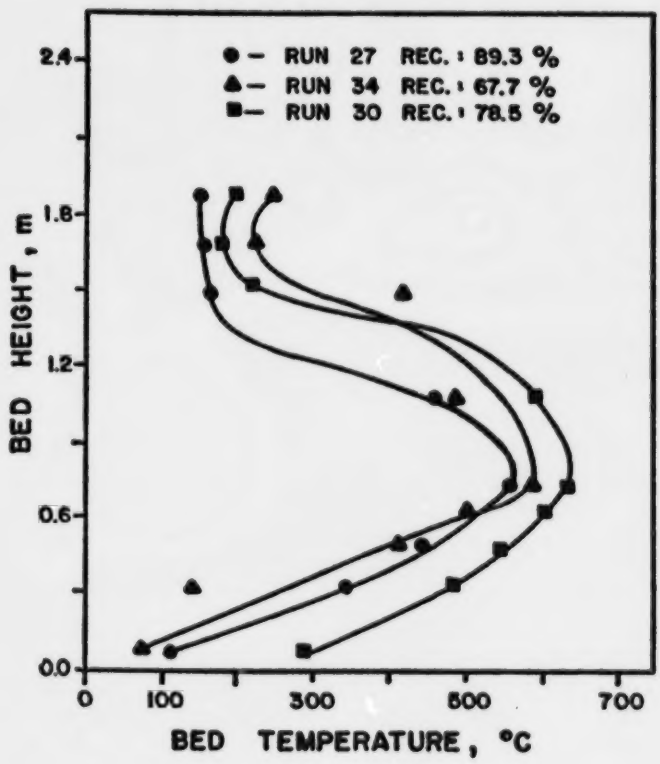


Fig. 9: Retort Temperature Profile for the Highest, the Lowest and an Intermediate Oil Recovery Indirect Retorting Runs Using Shale 2

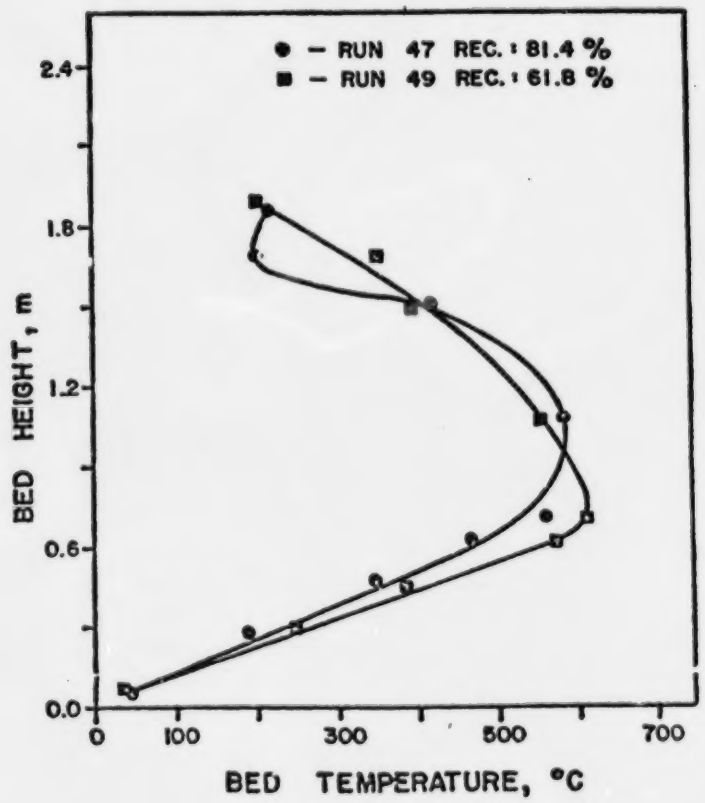


Fig. 10: Retort Temperature Profile for the Highest and the Lowest Oil Recovery Direct Retorting Runs

the effect of shale residence time in the temperature zones, the retort was divided into five temperature zones, these from top to bottom are, a preheating zone up to 300°C, two heating/retorting zones 300-500°C and above 500°C, and two cooling zones 500-300°C and below 300°C. These temperature zones were chosen because N.B. shale starts to lose weight at approximately 300°C (7), and the maximum temperature obtained during a Fischer assay is 500°C. The residence time distribution for all experimental runs are given in Appendix B.

For indirect retorting of shale 1, it can be seen from Figure 11, that oil recovery increases sharply with the increase of shale residence time at the above 500°C temperature zone. At longer residence times, beyond those investigated in this test program, the curve will of course level out and oil recovery may even start to decrease. This seems to be the case for the direct retorting of shale 1, as shown in Figure 12, which despite the two scattered points, displays a clear relationship between oil recovery and the shale residence time above 300°C. This temperature zone represents the retorting, combustion and part of the cooling zone. For shale 2, however, no definit relationship could be detected between shale residence time at any temperature zone and oil recovery.

The residence time required for shale particles to reach the bulk gas temperature in each temperature zone was estimated by heat transfer calculations. Assumptions used for these calculations were that the heat of reaction inside the shale particles is negligible and that the shale has slab-shaped geometry. Table 16 shows the external heat transfer co-efficients for selected experimental runs.

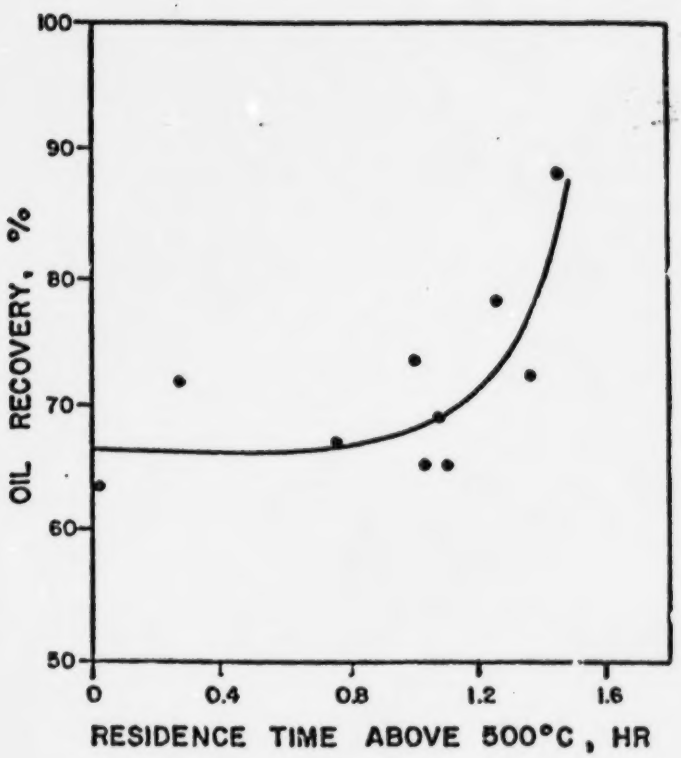
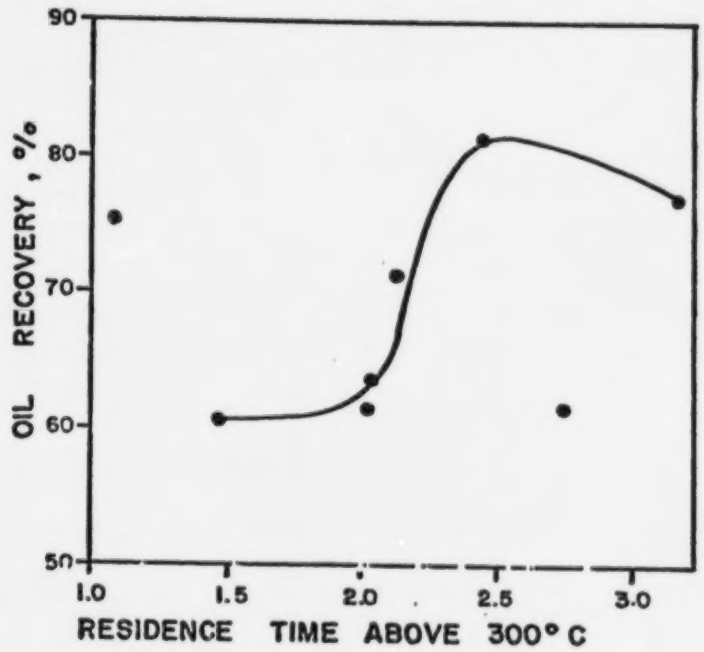


Fig. 11: Effect of Shale Residence Time above 500°C on Oil Recovery for Indirect Retorting



Ffg. 12: Effect of Shale Residence Time Above 300°C on Oil Recovery for Direct Retorting of Shale 1

TABLE 16

Calculated External Heat Transfer Co-efficients

Temperature ^{o}C	External Heat Transfer Co-efficient Btu/hr. ft.^{2} ^{o}F	
	Run 12	Run 13
300	13.5	14.4
400	14.2	15.1
500	14.8	15.9
600	15.5	16.5

The time required for the centre of a slab-shaped shale particle to reach the bulk gas temperature was also estimated from the general solution of the heat conduction equation (8), to be less than 4 minutes. The heat sink associated with the heat of pyrolysis was not taken into consideration. The actual time required for the center of the particle to reach the bulk gas temperatures will not be significantly different from those given above because the heat of pyrolysis is quite small, in the order of 200 Btu/lb.

From the above discussion it is clear that external heat transfer is not the limiting step, therefore residence time requirement must be dictated by the more complex kinetics of the pyrolysis process.

2.7.1.4 Effect of Shale Feed Rate

For indirect retorting feed rates of 16, 20 and 25 kg/hr have been investigated. It was found that, in general, a feed rate of 20 kg/hr tended to produce better oil recovery, therefore all direct experiments were carried out with a shale feed rate of 20 kg/hr.

Shale feed rate is one of the most important independent parameters which has a significant effect on the retort temperature profile

and shale residence time. Shale feed rates higher than 20 kg/hr gave rise to unfavourable temperature profiles and low peak temperatures. The low recovery at lower feed rates could perhaps be due to long residence times which could promote secondary cracking of product oil.

2.7.1.5 Effect of Gas Recycle Rate and its Distribution

Gas recycle rate and its distribution have a considerable effect on the oil recovery. For indirect retorting, Figure 13 shows the effect of the total gas recycle at a constant gas distribution of approximately 62% to the middle gas stream. Oil yield increased with an increase in recycle gas rate up to a maximum, after which oil yield starts to fall.

In order to explain this observation, runs 12 and 13 which registered the lowest and the highest oil recovery of 65.2 and 88.6%, respectively, were analyzed in terms of external mass transfer coefficients which is a function of gas velocity in the pyrolysis zone. The calculated mass transfer co-efficients in the temperature range of interest are shown in Table 17, which shows that the mass transfer coefficients changed by only 6.4 to 7.3%. Therefore, it is highly unlikely that the observed increase in oil recovery was due to increased external mass transfer coefficients. Other plausible explanations are: (a) A high recycle rate give rise to an even distribution of heat in the pyrolysis zone. (b) High recycle minimise oil cracking due to a reduction in products' residence time at elevated temperatures. (c) The drop in oil recovery at a very high recycle gas rate is possibly due to cooling down of the retort (temperature of the bottom recycle gas was only approx. $25^{o}C$).

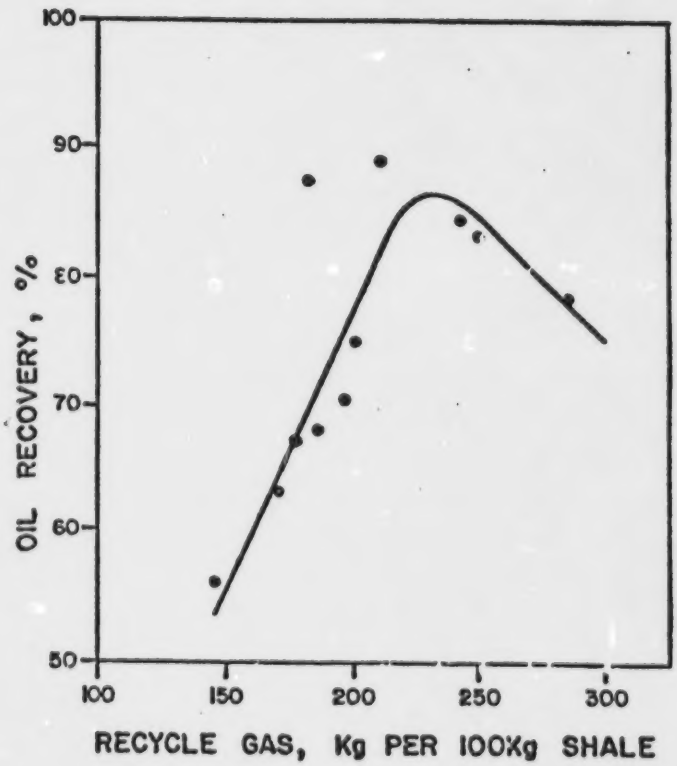


Fig. 13: Effect Recycle Gas|Shale Ratio on Oil Recovery

TABLE 17
Calculated Mass Transfer Coefficients

Temperature °C	Mass Transfer Co-efficient ft/hr		% Change
	Run 12	Run 13	
400	499.3	531.3	6.4
500	595.2	638.8	7.3
600	702.0	747.1	6.4

Recycle gas distribution requirement differs considerably according to the retorting mode, however, in both modes, high oil recovery coincides with high total recycle gas rates. It can be seen from Tables 4 to 7, that for indirect retorting high oil yields were achieved at a bottom gas recycle in the range of 35% to 38% of the total recycle gas, while the corresponding values for direct retorting were in the range of 80% to 88%. It is important to notice, that in both retorting modes, bottom gas recycle assists in recovery of energy from the spent shale. The wide variation in the gas distribution for the two retorting modes could in part be due to large difference in peak temperatures. Also in case of indirect retorting if a large percentage of the gas is fed to the bottom stream this means a smaller portion is fed to the preheater, i.e. a low heat input to the retort and consequently low oil recovery as shown in the following section. In direct retorting however, total heat input is a function of air feed rate; also the total recycle gas would be available for combustion irrespective of the injection position.

2.7.1.6 Effect of Air Feed Rate and Heat Input

In direct retorting the air feed rate and its distribution have a significant affect on the rate of heat generation, retort temperature profile and on oil recovery. While, in the case of indirect retorting, the

corresponding parameter is the rate of heat input via the gas preheater.

The effect of air/shale ratio (air feed rate) at constant recycle gas/shale ratios of approximately 2.14:1 and 1.72:1 are shown in Figure 14. It can be seen from the figure that, the optimum air/shale ratio appears to be a function of the rate of gas recycle. Also, deviation from an optimum air feed rate leads to a low oil recovery which is probably due to the lack of sufficient heat or the consumption of product oil in case of too little or too much air, respectively.

The effect of air distribution between the bottom and the middle of the retort can be seen from the results summarized in Table 18.

TABLE 18
Effect of Air and its Distribution on Oil Yield
Mode: Direct Shale:1

Run No.	Total Air kg/100 kg of Shale	Air Split wt% Middle	Bottom	Total Recycle Gas kg/100 kg of shale	Retorting Recovery % F.A.
20	28.74	100	0	144	75.1
36	28.44	77	23	153	61.6
37	28.44	74	26	148	63.6

These results show that introducing air to the bottom of the retort resulted in a reduction in oil yields. Also, the temperature profiles for these particular runs, see Appendix D, show that runs 36 and 38 are characterized by a high spent shale discharge temperature, which can be considered as a wasted energy.

In indirect retorting, the temperatures of the middle recycle gas stream was varied in the range of 600 to 660^{o}C (higher gas temperatures could not be attained with the available electrical gas heater). However,

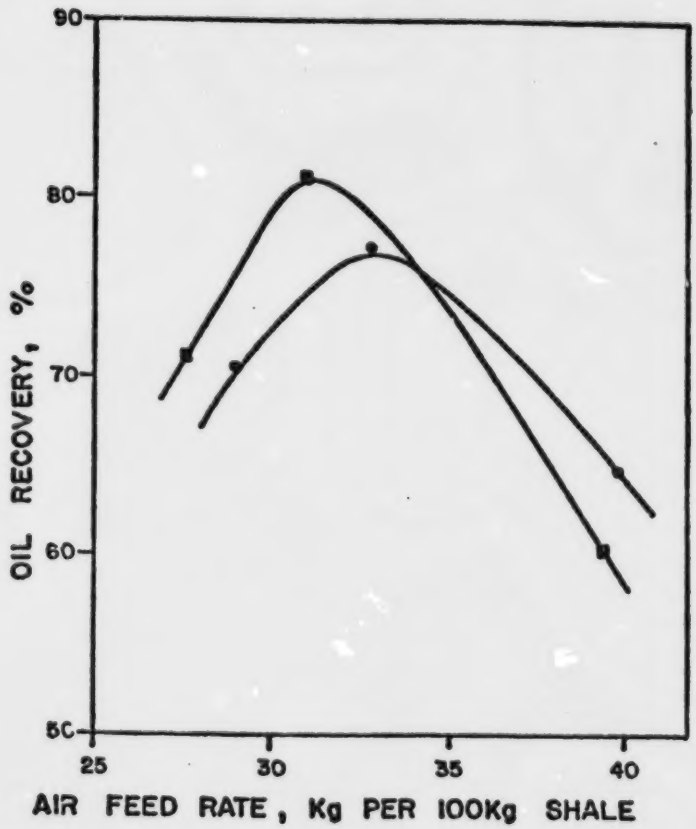


Fig. 14: Effect of Air Feed Rate on Oil Recovery at Different Gas/Shale Ratios: 2.14:1 and 1.72:1

the heat input to the retort was varied in the rate of 630 to 1,370 kJ/Kg of shale, this much wider variation was attained through variation in the recycle gas/shale ratio. For shale 1, oil yield showed strong correleation with the rate of heat input as shown in Figure 15. The equation of the straight line as determined by the least squares method is as follows:

$$Y = 53.02 + 1.93\ X$$

with a correlation co-efficient of 0.77.

As can be seen from Figure 16, Shale 2 oil recoveries do not show a correlation with the rate of that input to the retort.

2.7.2 Carbon Conversion

It has been observed by Furimsky et. al. (7) that organic carbon content of fresh shale and Fischer assay oil yield can be correlated by a linear relationship. Similar relationship can also be expected, between indirect mode oil recovery and organic carbon conversion. Ineeed, both shale 1 aod 2 show such a relationship which is shown in Fig. 17, however, shale 2 exhibit more scatter than shale 1.

This linear relationship can be expressed as follows:

$$Y = -5.616 + 1.37\ X$$

with correlation co-efficient 0.69.

For direct retorting however, there is no direct correlation between organic carbon conversion and oil yeild, such correlation is probably masked by varying degrees of combustion of the residual organic carbon.

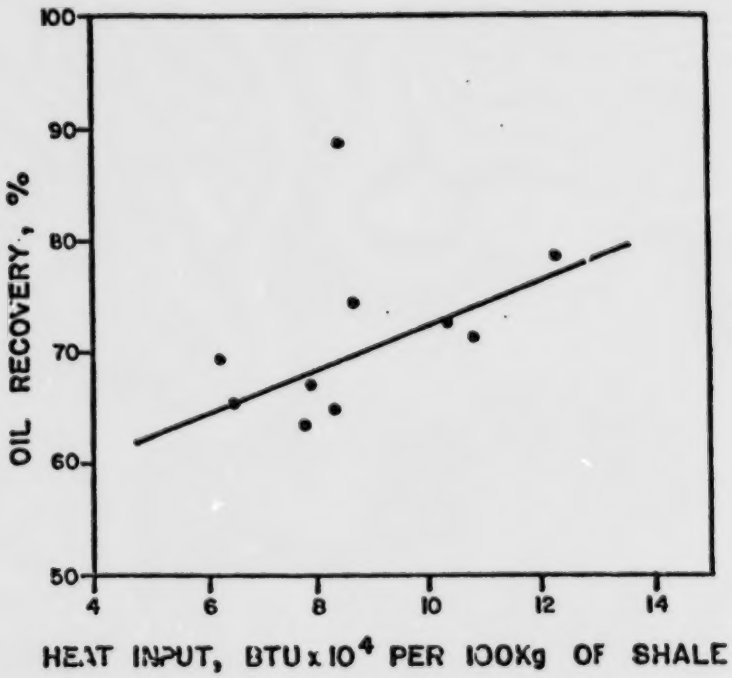


Fig. 15: Effect of Heat Input on Oil Recovery for Shale 1

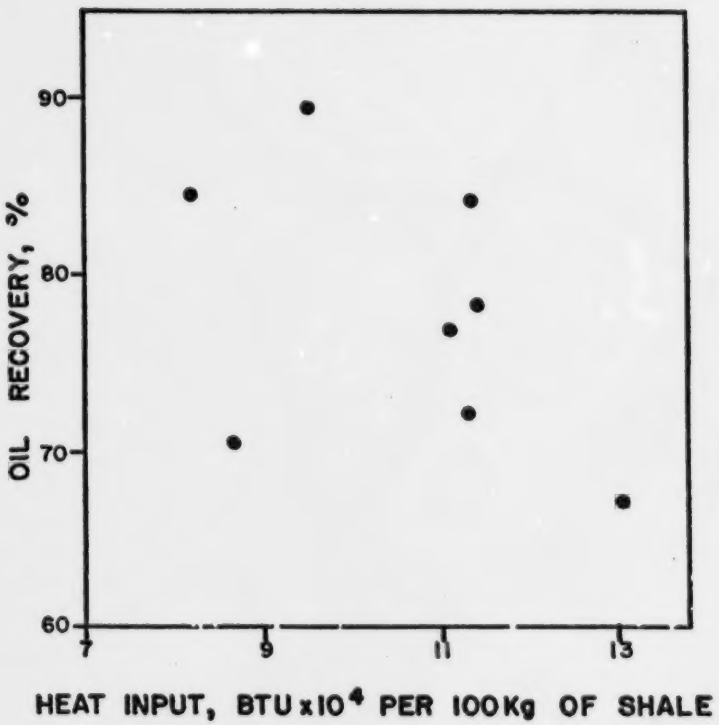


Fig. 16: Effect of Heat Input on Oil Recovery for Shale 2

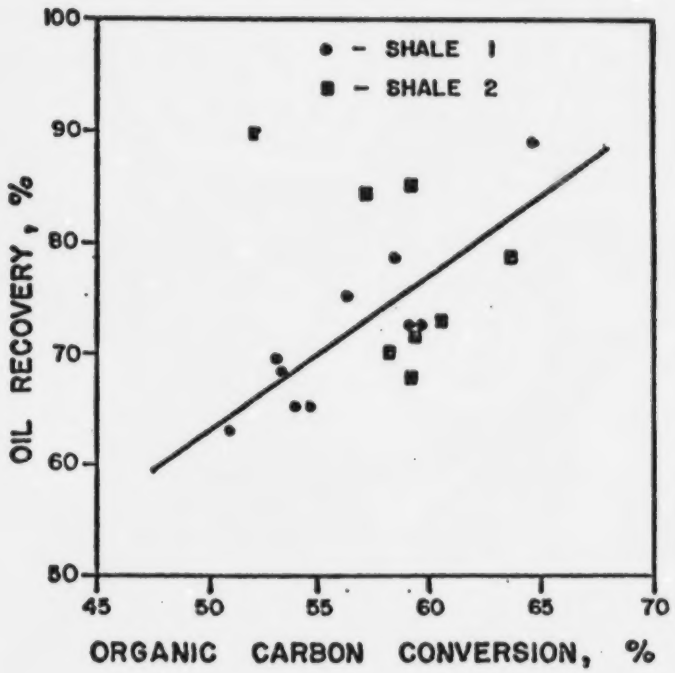


Fig. 17: Relationship Between Organic Carbon Conversion and Oil Recovery for Indirect Retorting

2.7.3 Product Quality

This section is intended as an assessment of the effect of shale grade and/or retorting mode on the physical and chemical properties of product oil, gas and spent shale.

2.7.3.1 Oil Properties

An inspection of the oil properties given in Tables 10 to 13, shows that shale oils produced from shale 1 by direct and indirect retorting are generally of a better quality than those produced from shale 2. The latter however have a marginally lower pour point and lower sulphur concentration than the former. On the other hand, nitrogen concentration displays the opposite trend to that of the sulphur, and since nitrogen is a much more difficult impurity to remove as compared to the sulphur, shale 1 must be considered the better feed stock.

As for the effect of the mode of retorting on oil properties, there is no detectable differences, exept perhaps, the hydrogen/carbon ratio is very marginally higher for oils produced by indirect retorting as compared to those produced by direct retorting. A more significant observation, however, is that there is no correlation between oil quality and the percentage of oil recovered i.e. high oil recoveries are possible without any sacrifice in oil quality.

The shale oil properties were also compared to those produced from Colorado shales. Table 19, shows four sets of data for N.B. shale oils representing the highest oil recoveries achieved for both shales using both retorting modes. Also given are two sets of data for Colorado shale oils. The table shows N.B. shale oil to be lighter as indicated by gravity and boiling ranges. It also has less sulphur and nitrogen impurities, therefore it would require less hydrotreating and consequently upgrading costs would

TABLE 19
Properties of Shale Oil Derived from New Brunswick and Colorado Shales

Run No.	API Gravity	Elemental Analysis wt% C	H	N	S	H/C Ratio	Pour Point °C	Flash Point °C	Kinematic Viscosity cSt at 50°C	Heating Value Btu/lb	Boiling Range °C IBP	50%	FBP
13	28.7	86.51	11.95	0.79	0.47	1.66	23.8	61.1	8.44	18504	95	370	604
27	21.8	86.46	11.90	1.16	0.28	1.64	15.6	74.4	13.40	18302	--	--	--
47	28.0	86.19	11.81	0.83	0.54	1.64	23.8	78.8	11.61	18770	143	380	565
44	25.5	86.18	11.56	1.28	0.22	1.61	12.8	76.7	14.10	18536	--	--	--
* Colorado Paraho, Direct (9)	21.4	84.5	11.2	1.29	1.96	1.59	23.8	85.5	--	--	63.0	423	593
* Colorado Paraho, Direct (10)	21.4	84.8	11.4	2.0	0.6	1.61	29.4	--	16.4	--	--	--	--
Saudi Arabian Crude	33.4	85	13.0	0.1	1.7	1.84	--	--	--	--	--	--	--

* See list of references

be lower.

2.7.3.2 Gas Composition and Calorific Value

The heating value of the gases obtained by direct retorting were in the range of 50 to 100 Btu/SCF, while the corresponding value for direct retorting were 77 to 152 Btu/SCF. The calorific value of indirect retorting gases are considerably low compared to those produced by similar processes such as the Paroho process. As mentioned earlier the reason for such low heating values is the infusion of air into the retorting gases, which result in dilution of the gases by inhert nitrogen.

Direct retorting product gas, as would be expected, have higher CO_2 concentration than indirect retorting gases. This of course is due to the combustion of residual carbon and possibly, higher degree of dissociation of carbonates due to higher peak temperatures. Full analysis of the product gases are given in Appendix D.

2.7.3.3 Spent Shale Composition and Heating Value

The calorific values of the spent shales were in the ranges of 467 to 536 Btu/lb, and 525 to 999 Btu/lb for direct and indirect retorting, respectively. The lower heating values for the direct retorting spent shales are of course due to the partial combustion of residual carbon. It is important to notice that the calorific values for the fresh shales tested were 2005 and 1700 Btu/lb for shale 1 and 2 respectively, therefore even for direct retorting the spent shale still contains a considerable fraction of the energy present in the fresh shale.

2.7.4 Process Performance

An important criteria for the assessment of a retorting process is the efficiency in converting fresh shale into oil and gas. This can be expressed as the percentage conversion of the input energy (calorific value

of the fresh shale) into useful forms of energy, i.e. oil and gas products. In the case of indirect retorting the external heat supply to the gas heater should be considered on the input side of the equation. For the same reason, if the energy in the spent shale is utilized, as is the case in the integrated system, the recovered energy should be credited to the output side of the equation.

The energy conversions for the highest oil yield runs representing both shales and both retorting modes are given in Table 20.

TABLE 20
Summary of Energy Conversion for the Highest Oil Yield Runs

Run No.	Shale Quality Gal/ton	Mode	Maximum Recovery % Fischer Assay	Energy Conversion % of Fresh Shale		
				Oil	Gas	Total
13	21.0	Indirect	88.6	57.9	5.4	63.3
27	15.5	Indirect	89.3	55.8	6.0	61.8
47	21.0	Direct	81.4	64.4	10.3	74.7
44	15.5	Direct	71.1	59.0	17.5	76.5

It can be seen from the table that, in direct retorting approximately 75% of the input energy was converted into oil and gas, compared to approximately 63% conversion in the indirect mode. Therefore, in terms of energy conversion, direct retorting is substantially better than indirect retorting, even though, the latter mode produced higher oil recovery. This of course remains valid unless the energy in the spent shale is recovered.

3.0 SPENT SHALE COMBUSTION EXPERIMENTS

3.1 Objectives

The primary objective of this sub-task was to assess the effectiveness of three spent shales obtained from the retorting of New Brunswick Albert County oil shales as sulphur capture media when co-combusted with high sulphur Minto coal in a fluidized bed combustor. The emphasis in the test program was on the determination of the effect of the spent shale/coal ratio (molar Ca/S ratio) on the emission of SO_2 as well as on the combustion efficiency.

3.2 Test Facility

Combustion trials were carried out in a 0.15 m fluidized bed combustor. The combustor and its accessories are shown schematically in Figure 18. The combustion chamber is made of SS 316 with an inside diameter of 0.15 m and a total height of 2.3 m. The bed depth was controlled by means of an adjustable bottom discharge pipe situated in the middle of the unit. Air was fed to the reactor through a distributor which consisted of 10 mushroom shaped tuyeres, each with 8, 0.79 mm holes. The exterior of the combustor was wrapped with electric resistance-type heating coils, necessary to bring the rig to operating temperature. Additionally an air preheater was utilized during start-up. A water cooling coil was located inside the chamber for the temperature control purposes.

Coal and spent shale were fed into the bed from individual screw feeders equipped with variable speed motors. Each feeder rested upon four load cells which provided an account of the solid feed rate. The feed stock was gravity fed into the combustor with a pneumatic assist.

Initially the combustor was equipped with three hot cyclones in series to minimize elutriation and to improve combustion efficiency. The collected

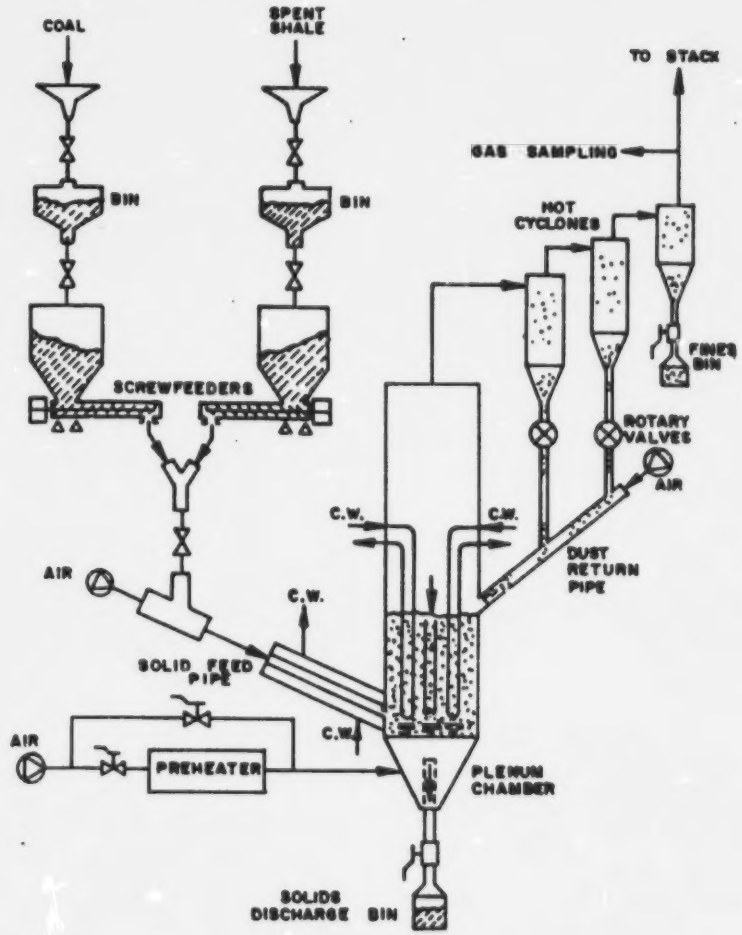


Fig. 18: Schematic of the Fluidized Bed Combustor and its Accessories

solids from the first two cyclones were recycled back into the combustor via a pair of rotary valves. A fourth cyclone was added in a later date in an attempt to minimise the dust loading in the flue gasses.

Monitoring of all input/output stream temperature pressures and flows, where applicable were undertaken. Flue gas analysis were obtained with continuous on-line analyzers for CO, CO_2, O_2 and SO_2. Data logging capability was also provided.

3.3 Experimental Procedure

Start-up was achieved by introducing the minimum air requirement to maintain fluidisation, followed by activation of the preheater and heating coils. Spent shale was then fed slowly into the combustors, the rate being gradually increased with time. At approximately 500^{o}C coal was introduced into the system and at 600^{o}C the water cooling coils was brought into operation to prevent a runaway reaction. Throughout this period the solid feed rates were increased toward their planned settings. At roughly 780^{o}C all external heating sources were cut and the shale/coal ratio was then adjusted to the desired setting. Bed temperature was then maintained at approximately 800^{o}C, by adusting the water flow to the cooling coils.

At one hour intervals the bottom discharge pot was emptied along with the fines from the two cyclone pots. All collections were weighed and saved for later chemical analysis. Temperatures, pressures, flow rates and remaining feed stock rates were also recorded. Every half hour gas analysis was recorded for comparison with the automatically logged information.

Following the first 3 runs it was found that there was some difficulty in maintaining freeboard temperature at its proper level due to poor insulation of the combustor walls, in subsequent runs the freeboard heating coils were left on throughout the test period.

3.4 Feed Stocks Characterization

Three batches of spent shales were prepared using the available spent shale resulting from the retorting experiments. The chemical analysis of the spent shales and the Minto coal used in this test program are given in Table 21. The three spent shales represented both parent shales and retorting modes. Spent Shale I, resulted from the direct retorting of shale 2, while spent shales II and III resulted from the indirect and direct retorting of shale 1, respectively. The particle size analysis of the coal and the spent shale are given in Table 22.

TABLE 22
Coal and Spent Shales Particle Size Analysis

Screen Size, mm (inch)	Fraction, wt%			
	Coal*	Spent Shales		
		I	II	III
- 3.36 + 2.83 (- 0.132 + 0.111)	0.1	2.87	0	0.06
- 2.83 + 1.41 (- 0.111 + 0.056)	44.48	41.75	31.98	31.20
- 1.41 + 0.354 (-0.056 + 0.014)	46.60	37.86	53.16	50.41
- 0.354 + 0.25 (- 0.014 + 0.01)	4.59	6.04	7.11	8.44
- 0.25 + 0.177 (-0.01 + 0.007)	2.90	4.62	4.02	4.98
- 0.177 fines (0.007 fines)	2.89	6.86	3.73	4.91
mean particle size, mm	0.79	0.82	0.66	0.65

* Average of two samples

The ash analysis of the spent shales as shown in Table 21, in particular calcium and magnesium oxide concentrations, differ from those of the parent shales as given earlier in Table 2. While some difference might be attributed to chemical reactions during the retorting process; the discrepancies are wide enough to suggest errors in the sampling and/or chemical analysis. This is particularly noticeable for spent shales II and III which originated from a common parent shale. The average value for the combined calcium and magnesium oxides concentration for spent shales II and

TABLE 21
Chemical Analysis of Coal and Spent Shales

	Coal*	Spent Shale I	Spent Shale II	Spent Shale III
Proximate Analysis (wt%)				
Moisture	0.81	0.33	0.5	0.65
Ash	16.6	93.74	87.60	83.56
Volatile Matter	33.8	4.6	12.5	17.2
Ultimate Analysis (wt%)				
Carbon - organic	67.3	3.39	5.76	5.27
- inorganic		1.22	0.45	1.22
Hydrogen	4.63	0.25	0.40	0.53
Nitrogen	0.72	0.15	0.24	0.28
Oxygen	3.46	0.43	4.21	7.95
Sulphur	7.29	0.82	1.34	1.19
Ash	16.6	93.74	87.60	83.56
Ash Analysis (wt%)				
SiO_2	28.8	63.03	57.17	54.14
Al_2O_3	19.3	14.32	14.81	15.12
Fe_2O_3	48.7	6.39	7.08	6.55
CaO	0.37	4.07	7.70	11.04
MgO	0.26	2.69	3.83	5.82
Na_2O	0.41	3.79	2.86	2.00
K_2O	0.60	1.92	1.81	1.63
S(as SO_3)	--	0.73	1.16	0.89
Gross Heating Value (Btu/lb)	12583	532	560	517

* Average of two samples

III is 14.2%, while the corresponding value for the parent shale is 14.27%. For these reasons; spent shale II and III were assumed to contain equal amounts of calcium and magnesium oxides equivalent to the calculated average value.

3.5 Results and Discussion

The main independant variables which influence the combustion efficiency and the level of SO_2 emission, are particle size, spent shale/coal ratio, fluidizing velocity, excess air, bed height, and the temperature of the bed and the freeboard.

The operating parameters tested in this study and the range of variations are given in Table 23, while Table 24 gives a summary of the operating conditions, measured and calculated parameters for all the experimental runs. As can be seen from these tables, the main emphasis in the test program was on the determination of the spent shale/coal ratio (molar Ca/S ratio) and bed depth on the level of SO_2 emission and the combustion efficiency. Bed temperature was regulated at $810 \pm 20\ ^{o}C$ which was the maximum safe temperature for the stainless steel combustor. A higher temperature in the order of $850^{o}C$ would improve both the combustion efficiency and SO_2 capture. Other operating parameters such as excess air and fluidising velocity were maintained for the majority of the experimental runs at 15-20% and 1.6 - 1.8 m/s, respectively, which are the ranges encountered in practical combustion systems.

TABLE 23
Range of Operating Conditions

Parameter		Range Tested
Shale/coal ratio		1.31 - 4.23
Fluidizing velocity	m/s	1.45 - 1.86
Excess air	%	11.7 - 23.9
Bed depth (fluidized)	m	0.58 & 0.75

TABLE 24
Summary of Test Conditions and Results

Parameter	Test Number 1	2	3	4	5	6	7	8	9	10	11	12	13
OPERATING CONDITIONS													
Coal feed rate (kg/hr)	3.6	2.6	3.3	3.4	3.6	3.1	3.5	3.3	3.6	3.0	3.1	3.1	2.6
Spent shale feed rate (kg/hr)	11.4	6.1	5.5	7.5	8.5	9.6	9.5	10.0	7.5	9.0	9.7	8.5	11.0
Spent shale batch	I	I	III	III	III	III	III	III	III	III	II	II	II
Air feed rate (m^3/hr)	32.34	26.81	29.89	29.46	32.16	26.03	32.33	31.86	36.14	25.85	32.10	30.41	27.43
Bed depth (m)	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.75	0.75	0.75	0.75	0.75
MEASURED PARAMETERS													
Bed Temperature (°C)	804	816	814	821	818	816	837	824	812	807	810	806	817
Freeboard temp: bottom (°C)	788	795	771	784	782	800	785	771	812	805	810	804	814
top (°C)	731	734	707	710	703	740	688	700	780	771	778	750	732
Cyclone temp. (°C)	668	667	676	671	666	691	672	679	729	727	732	699	695
Bed discharge kg/hr	8.4	6.5	4.6	5.7	6.7	7.9	6.8	6.3	5.5	6.8	7.8	6.2	7.8
Cyclone catch kg/hr	2.62	2.50	2.05	2.06	2.10	1.53	2.92	2.75	1.20	1.76	1.46	1.37	2.88
Flue gas composition CO%	0.42	0.87	0.024	0.51	0.69	0.07	0.58	0.26	0.46	0.13	0.16	0.20	0.14
CO_2%	15.1	15.1	14.8	15.6	15.3	15.4	15.3	14.6	15.6	16.0	16.9	16.4	16.2
O^2%	2.53	3.23	3.83	3.37	3.58	2.94	3.44	4.28	2.43	3.53	3.33	3.37	3.72
SO_2 PPM	2470	3250	2400	2560	2070	1860	2070	1780	1570	1060	588	510	354
CALCULATED PARAMETERS													
Fluidizing velocity (m/s)	1.80	1.16	1.68	1.67	1.82	1.47	1.86	1.81	1.79	1.66	1.80	1.70	1.55
Excess air %	12.2	15.7	23.5	18.1	19.8	15.0	18.9	23.9	11.7	19.1	18.4	16.6	19.8
Combustion efficiency %	85.1	74.3	84.3	82.7	83.3	78.0	85.5	85.2	89.9	92.6	91.9	87.5	85.6
Shale/coal ratio	3.17	2.35	1.67	2.21	2.36	3.10	2.71	3.03	2.08	3.00	3.13	2.74	4.23
Molar Ca/S ratio	1.75	1.31	1.65	2.14	2.27	2.90	2.58	2.85	2.03	2.82	3.22	2.84	4.24
SO_2 reduction %	60.9	53.70	62.3	62.3	68.7	74.3	68.1	71.7	76.2	82.7	89.6	91.3	93.7

The effect of molar Ca/S ratio and bed depth on SO_2 reduction is illustrated in figure 19. The figure shows that at molar Ca/S ratio of approximately 3:1, SO_2 reduction for the shallow bed is approximately 75%; this rose to 90% for the deeper bed. The combustion efficiency was also affected by bed depth. The average combustion efficiencies were 82% and 92% for the shallow and deep beds respectively. These effects could be attributed to longer residence time in the deeper bed.

The relatively low combustion efficiencies were partly due to the high ash content in the spent shale and high spent shale/coal ratios of up to 4.3:1 which were required to achieve the desired Ca/S ratio. Other factors include a residence time in the freeboard of less than 1 sec. and low freeboard temperature due to poor insulation. The main carbon loss was in the fly ash as can be seen from Table 25, can contain up to 17% carbon compared to bottom ash carbon content of less than 1%.

The calorific value of the spent shales used were in the range of 517 to 560 Btu/lb. At a spent shale/coal ratio of 4:1 this represents 15 to 20% of the thermal output of the combustor.

The above discussion shows clearly that spent shales can be used effectively to reduce SO_2 emission from high sulphur coal and that it makes a significant contribution to the overall thermal efficiency of the process.

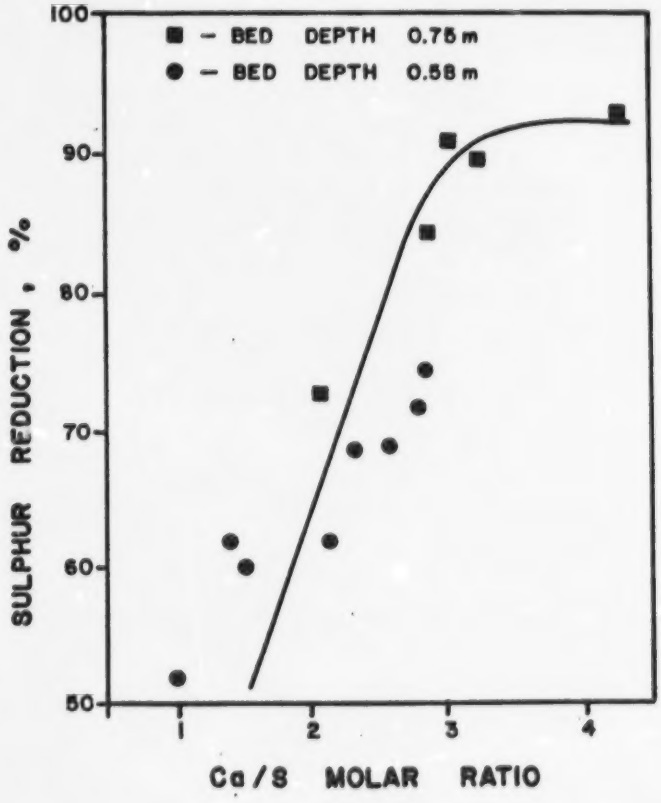


Fig. 19: The Effect of Bed Depth and Ca/S Ratio on Sulphur Reduction

TABLE 25
Chemical Analysis of Cyclone Catch and Bed Discharge

Parameter		Test Numbers 1	2	3	4	5	6	7	8	9	10	11	12	13
Cylone catch	Total carbon, wt%	11.5	16.4	16.1	17.8	17.9	16.7	11.4	11.7	14.3	7.91	9.21	11.8	8.79
	Organic carbon, wt%	10.5	15.2	15.1	17.1	15.9	15.5	9.91	11.6	13.2	8.05	9.44	11.4	8.29
	Total sulphur, wt%	1.01	1.05	1.56	1.47	1.45	1.38	1.58	1.64	1.43	1.61	1.70	1.75	1.68
Bed discharge	Total carbon, wt%	1.01	1.71	1.64	1.97	1.80	4.31	1.43	1.20	1.46	0.77	1.07	1.74	1.25
	Organic carbon, wt%	0.99	1.81	1.35	1.82	1.89	3.82	1.33	1.17	1.38	0.68	0.83	1.45	0.92
	Total sulphur, wt%	1.62	1.58	2.64	2.58	2.42	2.44	2.32	2.38	2.48	2.45	2.57	2.43	2.32

4.0 INTEGRATED SYSTEM EXPERIMENTS

The concept of an integrated fluidized bed combustor and an oil shale retort system have been described earlier, see Section 1 and Figure 1. The integration of the two reactors described earlier was carried out and the system was operated in a fully integrated mode for short periods of time, not sufficient however, to obtain meaningful results. This was due to operational problems steming from a high oxygen concentration and a high dust loading in the flue gas from the combustor, coupled with inherent limitations in the design of the fluidised bed, which was not intended for this specific application.

Over a period of two months including three weeks of 24 hr operation, several attempts have been made to solve the above mentioned problems. The high oxygen concentration problem was due to operating the combustor on high excess air in an effort to control bed temperature. This problem was readily solved by re-design of the cooling system and increasing the surface area of the water cooling coils. The main difficulty however, was caused by the high dust loading in the flue gases. This has led to plugging of the retort distributor pipes and consequently a backpressure of up to 5 psig on the atmospheric combustor. This pressure, although not excessive, was sufficient to cause difficulties such as bursting of combustor gaskets due to combinations of backpressure and high temperature. The latter led to metal creep and elongation of the bolts holding the combustor shell together. Attempts to solve these problems included re-design of the retort distributor pipes, installation of additional cyclone and screening out of fine feed material to eliminate most of the fine particles. This effort was partially successful but as mentioned earlier, did not results in the extended uninterrupted operation which is required to obtain the desired results.

The integrated system is technically feasible and offers potential substantial improvement in the economics of the retorting processes. This view is supported by the results of this study. For example, Figure shows that no less than 30% of the energy in the fresh shale remains in the spent shale. This together with 5 to 10% of the energy in the form of product gas, as well as shale fines, could add up to 50% of the energy in the original shale. This energy would be lost in conventional retorting processes. The effectiveness of spent shale as a sulphur capture medium has also been demonstrated.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This section deals with the general conclusions which have emerged from this work and seeks to point to future research and development work.

5.1 Conclusions

The main conclusions of this investigation are as follows:

a) The retorting characteristics of New Brunswick Albert Mines shales have been studied in both direct and indirect retorting modes. Oil recoveries of 81% and 90% have been achieved in the direct and indirect modes, respectively.

b) The effect of the independent operating parameter such as bed height, shale feed rate, recycle gas rate and distribution, air feed rate, etc., on the oil recovery have been identified. It was shown that shallow beds of less than 1.75 m produced substantially higher oil yields than deeper beds. Recycle gas rate and its distribution between the bottom and middle recycle streams was shown to have a significant impact on oil recovery. For both retorting modes high oil recovery was achieved at a high total recycle gas rate in the order of 2 kg of gas per kg of shale feed,

while the gas requirements for the middle recycle stream were in the range of 62% to 65% and 15% to 20%, for the indirect and direct retorting modes, respectively. Air feed rates of 0.3 kg/kg of shale produced the highest oil recovery, also the introduction of air to the bottom recycle stream adversely affected the oil yield. Retort temperature profile and in particular the retorting zone profile was shown to have a significant effect on the oil yield.

c) The two shales tested varied in their retorting characteristics. However, the oil recovery was shown to be independent of the shale grade and high oil recoveries were achieved for both shales at not too dissimilar sets of operating conditions.

d) The product oil quality was shown to be independent of oil recovery. There are however variations in the oil quality depending on the shale. Oils from shale 1 were found to be of better quality than these from shale 2.

e) The overall quality of New Brunswick shale oil is better than Colorado shale oil.

f) In direct retorting mode 75% of the energy in the fresh shale was converted into oil and gas, while for indirect retorting only 63% of the input energy was converted into products.

g) Spent shales retained no less than 30% of the energy in the fresh shale. Spent shales was also shown to be an effective sulphur capture media when burnt with high sulphur coal in a fluidised bed combustor. Sulphur reduction in excess of 90% has been achieved at a molar Ca/S ratio of 3:1.

5.2 Recommendations

Although the retorting of New Brunswick shales in the direct and indirect modes, and fluidised bed combustion of high sulphur coal and spent shale were successfully demonstrated, full integration of the system remains to be demonstrated. Further R & D work is also required for the improvement of products yields, better understanding of retorting characteristics of New Brunswick shales and to demonstrate the potential advantages of the integrated system. The main recommendations are as follows:

a) Demonstrate the operation of the fully integrated fluidized bed combustion retorting system: Equipment changes will have to be carried out in order to avoid the difficulties encountered under the present contract.

A submission for further work has already been made to CANMET under the Energy Conversion Cost Shared Program 1985-86. The RPC proposal AS/85/16-P of November 18, 1984 "Modification of Existing Integrated Oil Shale Retort System and Assessment of its Advantages Compared to Conventional Retorting Systems", has been assigned DSS number 15SQ.23440-4-9159X.

As indicated by the title of the above proposal, potential improvements in overall energy efficiency of the retorting process which might arise from the integrated system should be assessed. The integrated system process will also be optimised in terms of overall energy efficiency and product slate.

b) Further optimization of the retorting process requires fundamental studies on representative shale samples. This will include physical properties such as porosity, pore size distribution, specific heat, thermal conductivity, and thermogravimeteric analysis. Small scale retorting studies are necessary to ascertain the effect of retorting gas

composition including the effect of steam injection on the products yields and slate.

c) An economic evaluation of the cost of liquid products from the Albert County Mines should be carried out based on current knowledge of the resource and process technology.

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7.0

AUTHORIZATION

DEPARTMENT: Applied Sciences

PROJECT TITLE: Demonstration of an Integrated Oil Shale Retort System

PROJECT NUMBER: 50199

PROPOSAL NUMBER

REPORT AS/85/51

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8.0 APPENDICES

APPENDIX A

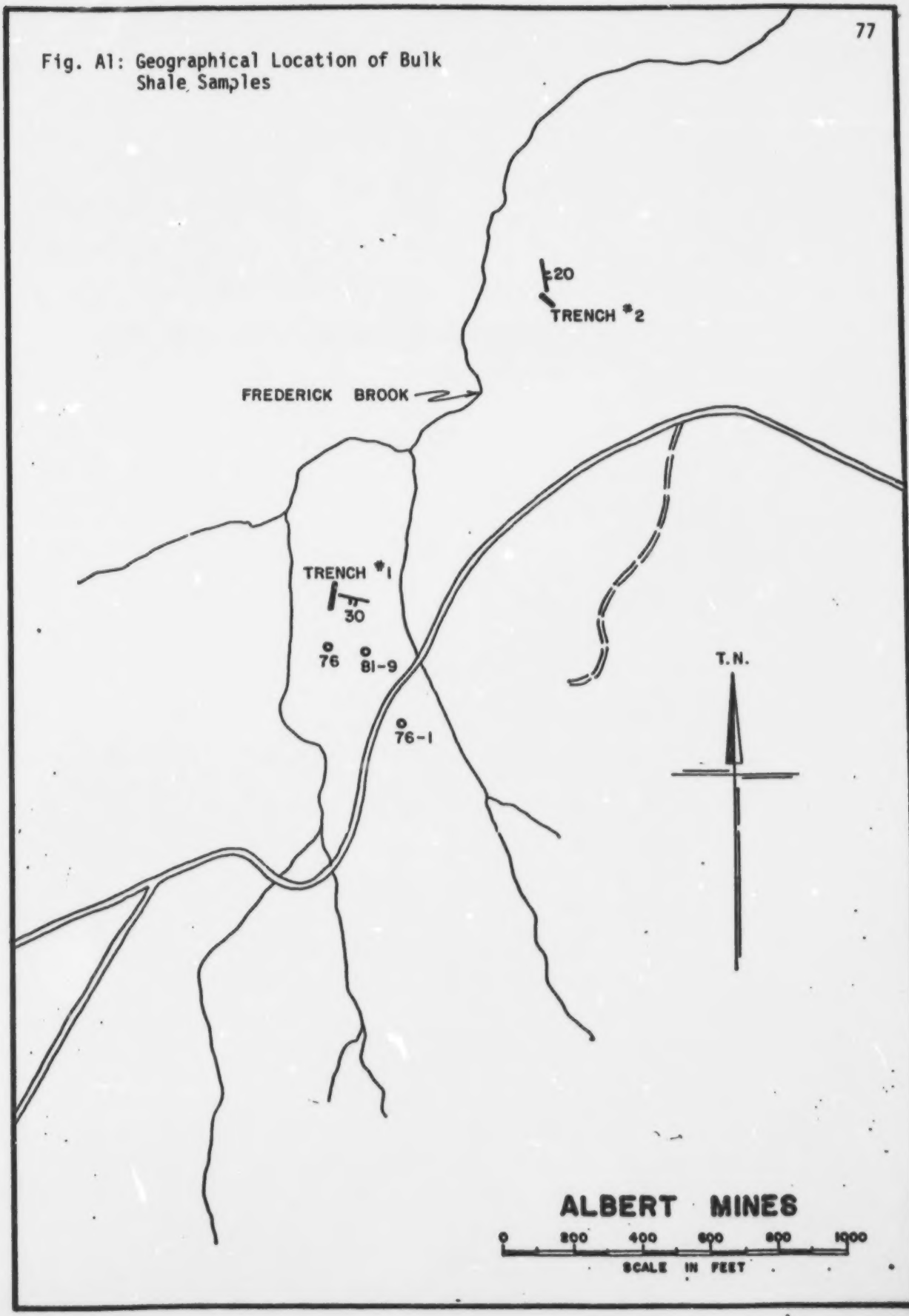
Shale Origin and Geological Information

The information contained in this Appendix has been supplied by Mr. Clint St. Peter of Department of Natural Resources, Government of New Brunswick

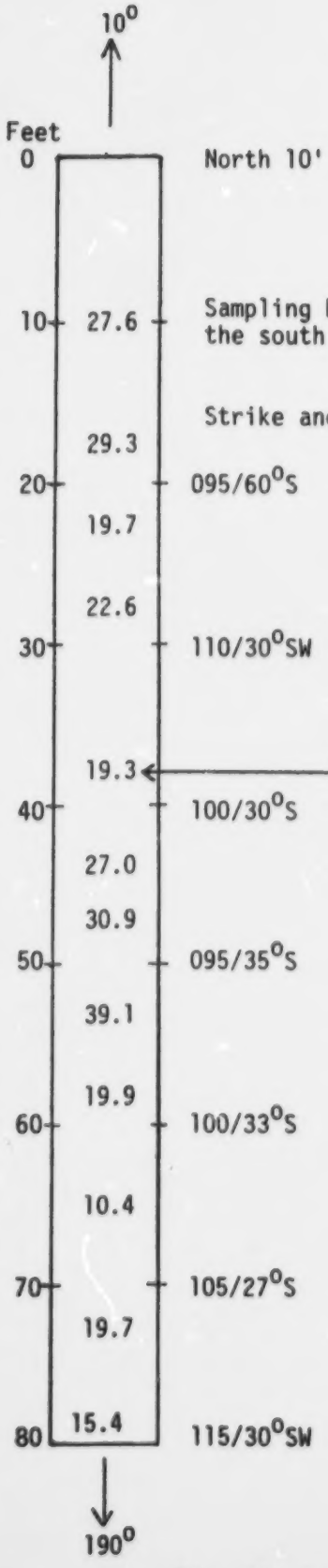
Shale Origin and Geological Information

The geographical location of the two trenches from which bulk samples for the retorting were taken is shown in Fig. A1. Sketches of both trenches together with pertinent geological information are shown in Fig. A2 and A3. Also incorporated in the Figures are the Fischer Assay Oil yield of samples taken at regular intervals along the length of the trench. Shale 1 and 2 referred to in the text correspond to trench 1 and 2 respectively.

Fig. A1: Geographical Location of Bulk Shale Samples



Trench No. 1



North 10' filled with water, therefore, not sampled for assay

Sampling begins, sample interval 3' and proceeded towards the south end of the trench

Strike and Dip Bedding

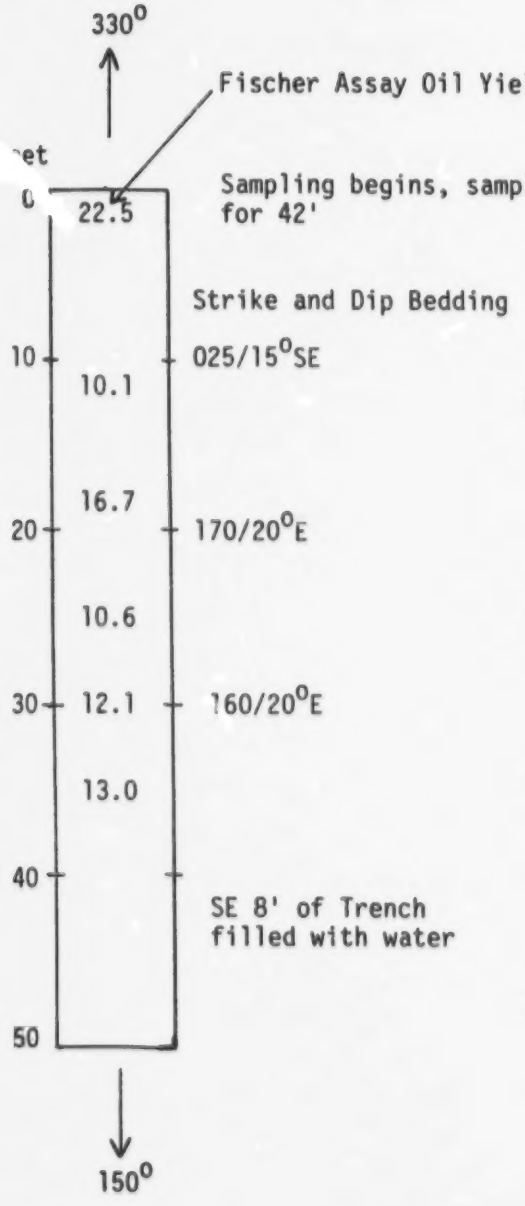
Fischer Assay Oil Yield, Imp gal/ton

NOTES:

1. Overburden about 2' from 0 to 60 feet. From 60 foot mark to south end of trench overburden is about 4 feet.
2. South end of trench lies 165 feet on a bearing 320° from Canadian Oxy hole 81-9.
3. After overburden removal, the rock here can be excavated with a backhoe.
4. Rock-type: brown-weathering, flexible, fissile shale. Rock consists of alternating micro-laminations (0.05 to 0.2mm) of kerogenous dolomitic and silty dolomitic layers. Rock is soft.
5. About 35 stratigraphic feet exposed in trench.

Fig. A2: Geological and Other Information on Trench No. 1

Trench No. 2



NOTES:

1. Overburden less than 2 feet. Outcrop present on logging road on NW end of trench before trench was opened.
2. After overburden removal, the rock will require ripping before it can be excavated. The rock is too competent to remove by backhoe.
3. Rock-type: Brown-weathering, subfissile silty shale. Rock has 0.5 to 2 mm thick laminations of dolomitic silty shale and dolomitic kerogenous shale. The kerogen laminations are disrupted and discontinuous.
4. About 5 stratigraphic feet exposed in trench.

Fig. A3: Geological and Other Information on Trench No. 2

APPENDIX B

Distribution of Shale Residence Time for All Runs

TABLE 17
Distribution of Shale Residence Time
Set 1
Mode: Indirect Shale: 1

Run No.	Total Residence Time (hr)	Residence Time Distribution, hr					
		Up to 300°C	300-500°C	Above 500°C	500-300°C	Less than 300°C	Oil Recovery
11	4.34	0.49	1.16	1.37	1.32	--	72.6
12	3.45	0.44	0.85	1.10	1.06	--	65.2
13	4.05	0.77	0.48	1.43	0.95	0.42	88.6
14	3.15	0.42	0.51	1.04	0.85	0.33	65.3
15	3.91	0.58	0.69	1.06	0.95	0.63	69.0
16	4.5	0.26	1.66	0.0	1.66	0.92	63.3
17	4.73	0.46	0.63	0.26	2.41	0.97	72.8
21	4.89	0.83	0.83	1.26	1.32	0.65	78.5
22	3.78	0.55	0.63	1.0	0.95	0.65	74.5
23	3.15	0.53	0.59	0.76	0.80	0.47	67.5

Table 18
Distribution of Shale Residence Time
Set 2
Mode: Indirect, Shale: 2

Run No.	Total Residence Time (hr)	Residence Time Distribution, hr					
		Up to 300°C	300-500°C	Above 500°C	500-300°C	Less than 300°C	Oil Recovery
27	3.73	0.45	0.56	1.19	0.90	0.63	89.3
28	4.05	0.24	0.90	1.43	1.06	0.42	70.2
29	4.22	0.37	0.47	2.27	0.79	0.32	84.9
35	4.28	0.05	0.90	1.85	0.74	0.74	84.3
32	5.36	0.53	0.83	2.35	1.12	0.53	72.5
34	5.19	0.23	0.93	2.05	0.86	1.12	67.7
30	3.41	0.32	0.34	2.03	0.55	0.17	78.5
31	3.34	0.25	0.34	2.05	0.51	0.19	72.7

TABLE 19

Distribution of Shale Residence Time

Mode: Direct
Shale: 1

Run No.	Total Residence Time, hr.	Residence Time Distribution, hr					
		Up to 300°C	300-500°C	Above 500°C	500-300°C	Less than 300°C	Oil Recovery
18	3.78	1.03	1.11	0.37	0.74	0.53	60.4
20	3.20	0.87	0.68	0.38	0.42	0.85	75.1
36	4.10	0.61	1.48	0.53	0.53	0.95	61.6
37	4.02	0.56	1.80	0.24	0.53	0.89	63.8
46	4.60	0.16	1.85	1.32	0.48	0.79	77.3
47	4.10	0.0	1.64	0.77	0.58	1.11	81.4
48	3.86	0.0	1.27	0.85	0.45	1.29	71.4
49	4.26	0.0	1.08	1.67	0.56	0.95	61.8

TABLE 20
Distribution of Shale Residence Time

Mode: Direct
Shale: 1

Run No.	Total Residence Time, hr.	Residence Time Distribution, hr: Up to 300°C	300-500°C	Above 500°C	500-300°C	Less than 300°C	Oil Recovery
41	4.60	0.11	1.77	1.22	0.56	0.94	63.9
42	4.60	0.05	2.01	1.11	0.48	0.95	59.3
43	4.60	0.11	2.09	1.0	0.56	0.84	58.5
44	4.18	0.03	1.98	0.85	0.53	0.79	71.1
45	4.47	0.0	2.33	0.85	0.45	0.84	65.3

APPENDIX C

Summary of Experimental Conditions and Oil Recovery of Initial Trial Runs

Summary of Experimental Conditions and Oil Recovery of Initial Trial Runs

Shale 1
Mode: Direct and Indirect

Run No.	Mode	Feed Rate kg/hr	Average Bed Height m	Shale Residence Time hr	Total Recycle Gas kg/100 kg of shale	% Distribution* in the middle	Air kg/100 kg of shale	% Distribution in the middle	% Oil Recovery
2	Direct	27.2	2.27	4.42	104.8	20.4	59.0	100.0	42.0
3	Direct	28.4	2.27	4.22	79.0	32.0	49.0	100.0	40.3
5	Direct	24.0	2.26	4.98	79.0	17.4	45.1	100.0	37.0
7	Indirect	16.0	2.25	7.43	223.0	53.0	--	--	28.4
8	Indirect	16.0	2.23	7.37	218.0	87.0	--	--	41.8
9	Indirect	16.0	2.27	5.00	152.0	91.0	--	--	42.9

* Remaining percent of total recycle gas was introduced at the bottom of the retort

APPENDIX D

Temperature Profiles and Computer Outputs
Listing Experimental Conditions
and Results of all the Experimental Runs

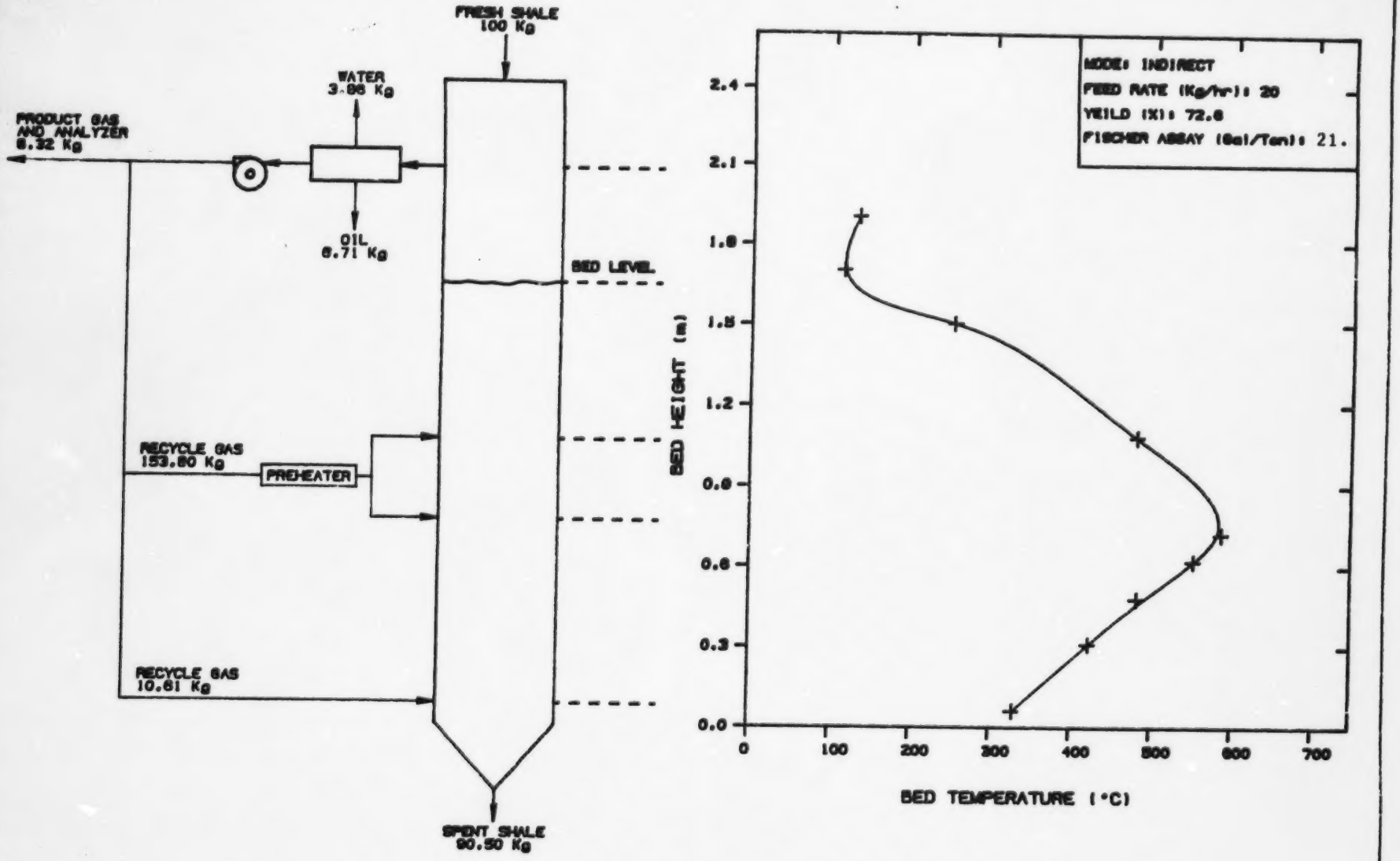


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 11

EXPERIMENT NO:11 SHALE NO: 1

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.64
FEED RATE, KG/HR: 20.00
DURATION, HR: 17.00
RESIDENCE TIME IN HR: 4.34
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.64
RECYCLE GAS SPLIT, %: BOTTOM: 6.5 MIDDLE: 93.5

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: 1.72
TOTAL INPUT: 101.72

OUTPUT IN KG

SPENT SHALE: 90.50
EXHAUST GAS: 0.
ANALYZER INTAKE: 8.32
OIL PRODUCED: 6.71
WATER FORMED: 3.86
TOTAL OUTPUT: 109.39
% UNACCOUNTED: -7.54

BOTTOM RECYCLE GAS, KG: 10.61
MIDDLE RECYCLE GAS, KG: 153.80

GAS ANALYSIS IN MOL %

H2: 3.76
N2: 81.48
O2: 1.19
CO2: 6.07
CO: 3.85
CH4: 0.56
C2: 1.06
C3: 1.980
C4: 0.050

BTU PER SCFM: 104.60

DISTRIBUTION OF ORGANIC CARBON
% OIL 49.73
% SPENT SHALE: 36.06
% GAS: 4.99

% UNACCOUNTED CARBON: 9.22

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 50.40
GAS: 4.42
SPENT SHALE: 19.20

YIELD, % OF F.A: 72.60

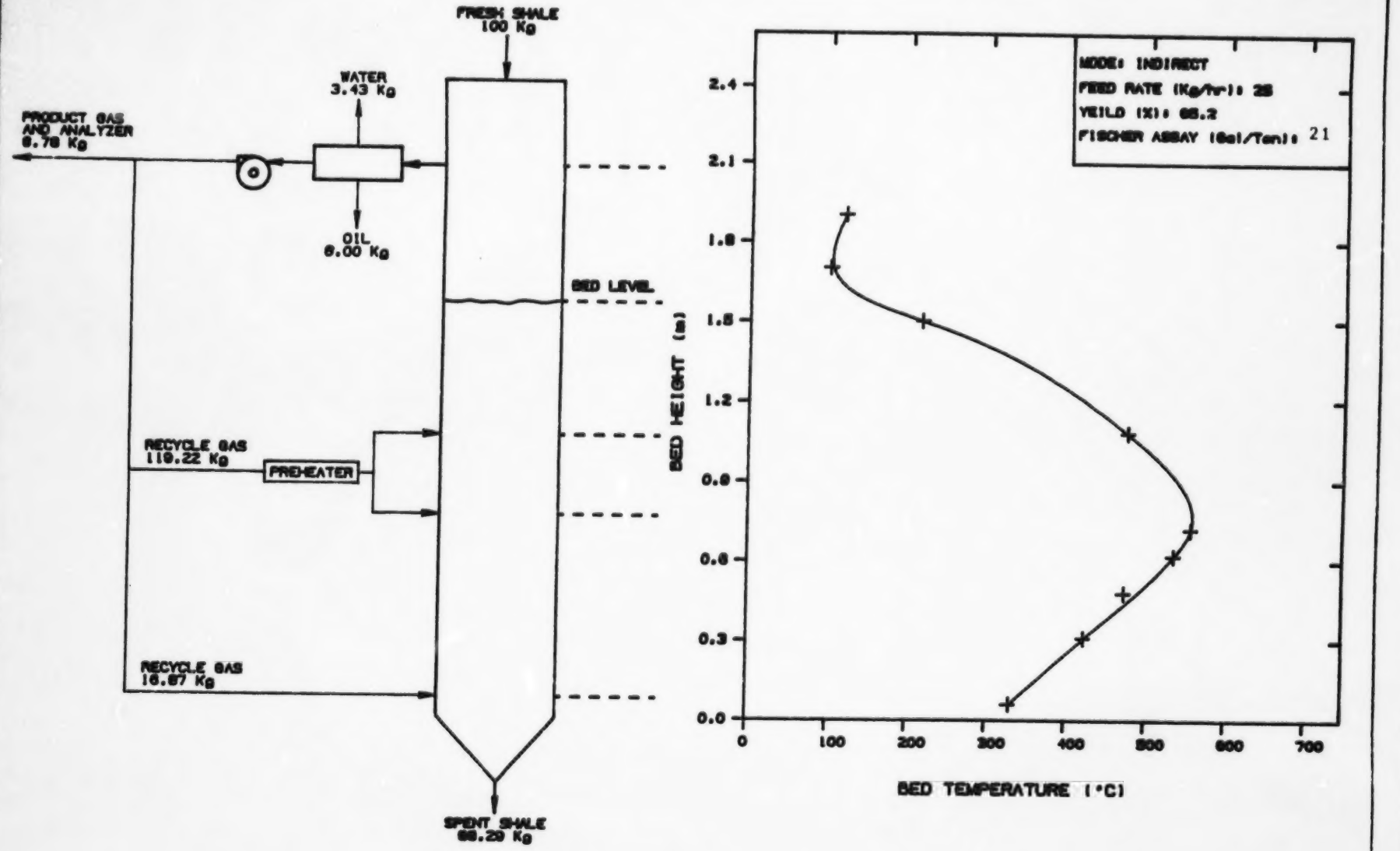


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 12

EXPERIMENT NO:12 SHALE NO: 1

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.63
FEED RATE, KG/HR: 25.00
DURATION, HR: 17.00
RESIDENCE TIME IN HR: 3.45
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.33
RECYCLE GAS SPLIT, %: BOTTOM: 12.4 MIDDLE: 87.6

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: -1.03
TOTAL INPUT: 98.97

OUTPUT IN KG

SPENT SHALE: 88.29
EXHAUST GAS: 0.
ANALYZER INTAKE: 6.63
OIL PRODUCED: 6.00
WATER FORMED: 3.43
TOTAL OUTPUT: 104.35
% UNACCOUNTED: -5.43

BOTTOM RECYCLE GAS, KG: 16.49
MIDDLE RECYCLE GAS, KG: 116.86

GAS ANALYSIS IN MOL %

H2: 4.10
N2: 79.15
O2: 1.17
CO2: 5.46
CO: 4.96
CH4: 0.56
C2: 2.39
C3: 2.010
C4: 0.200

BTU PER SCFM: 138.67

DISTRIBUTION OF ORGANIC CARBON
% OIL 45.72
% SPENT SHALE: 40.85
% GAS: 4.90

% UNACCOUNTED CARBON: 8.53

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 48.77
GAS: 5.03
SPENT SHALE: 21.22

YIELD, % OF F.A: 65.20

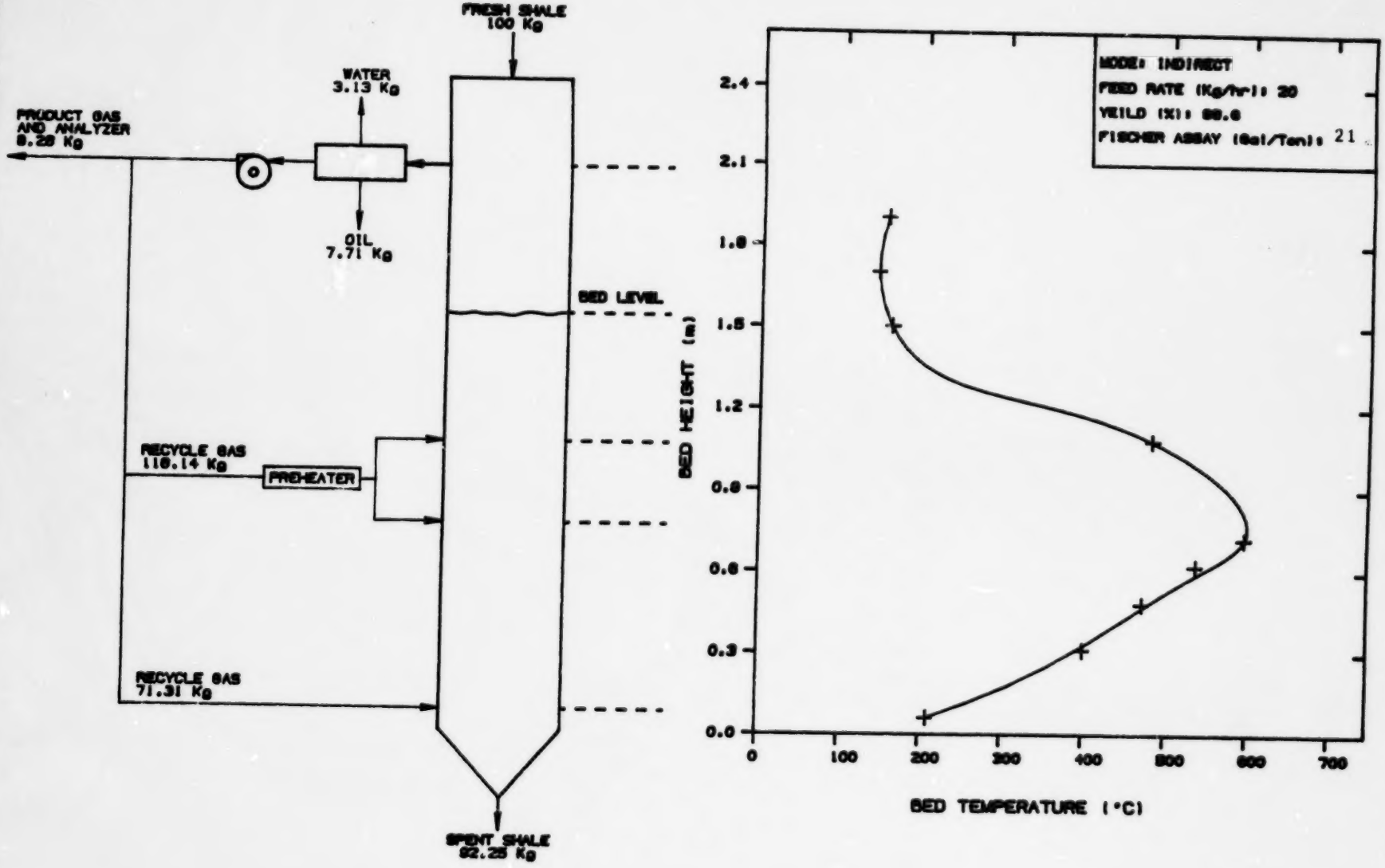


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 13

EXPERIMENT NO:13 SHALE NO: 1

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.53
FEED RATE, KG/HR: 20.00
DURATION, HR: 13.00
RESIDENCE TIME IN HR: 4.05
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.87
RECYCLE GAS SPLIT, %: BOTTOM: 38.0 MIDDLE: 62.0

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: 5.05
TOTAL INPUT: 105.05

OUTPUT IN KG

SPENT SHALE: 92.25
EXHAUST GAS: 0.
ANALYZER INTAKE: 8.26
OIL PRODUCED: 7.71
WATER FORMED: 3.13
TOTAL OUTPUT: 111.36
% UNACCOUNTED: -6.00

BOTTOM RECYCLE GAS, KG: 71.31
MIDDLE RECYCLE GAS, KG: 116.14

GAS ANALYSIS IN MOL %

H2: 4.30
N2: 79.35
O2: 1.30
CO2: 6.00
CO: 4.16
CH4: 1.11
C2: 1.70
C3: 2.030
C4: 0.050

BTU PER SCFM: 125.81

DISTRIBUTION OF ORGANIC CARBON
% OIL 55.38
% SPENT SHALE: 37.90
% GAS: 5.72

% UNACCOUNTED CARBON: 1.00

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 57.92
GAS: 5.39
SPENT SHALE: 20.41

YIELD, % OF F.A: 88.60

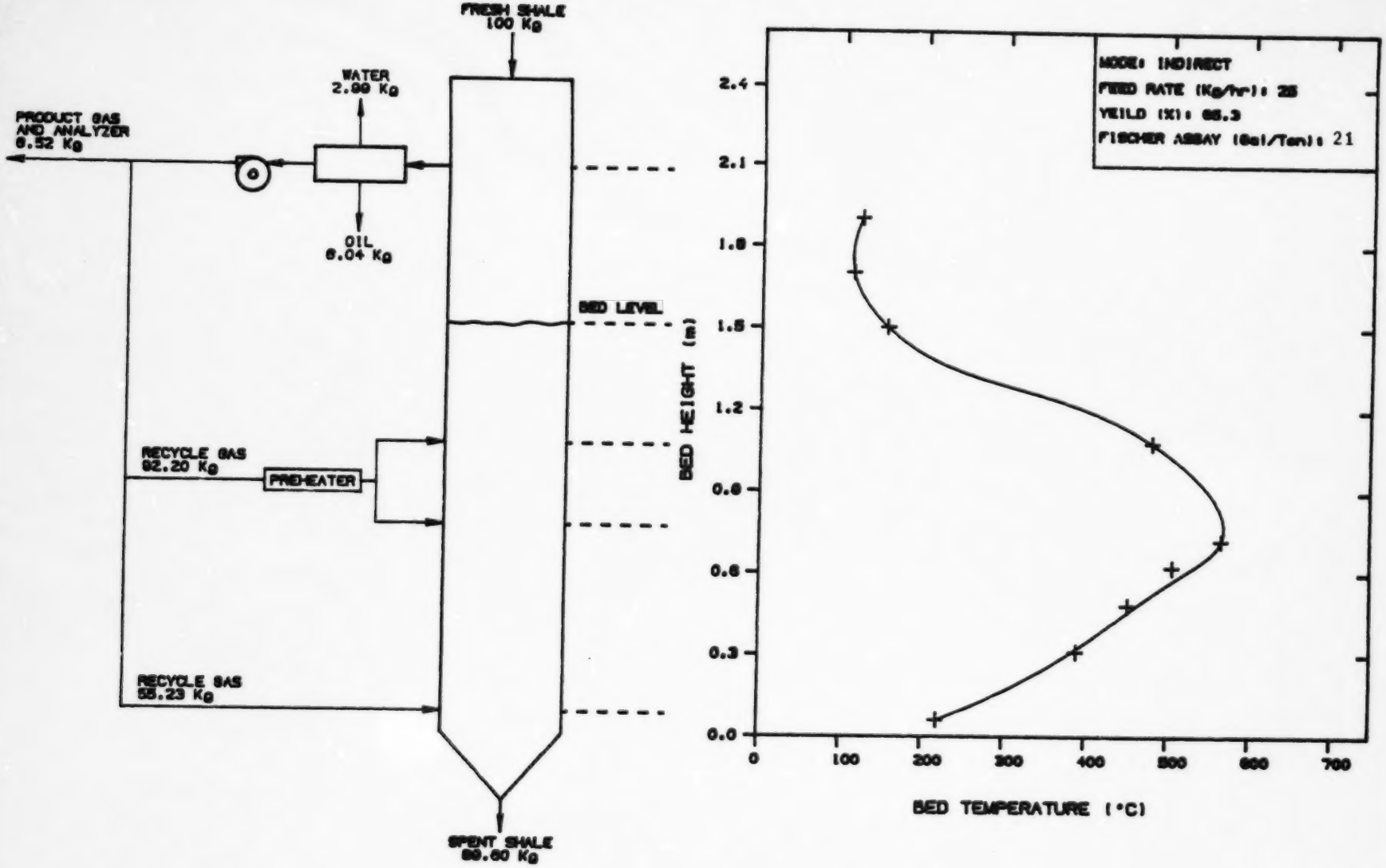


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 14

EXPERIMENT NO:14 SHALE NO: 1

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.49
FEED RATE, KG/HR: 25.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 3.15
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.47
RECYCLE GAS SPLIT, %: BOTTOM: 37.5 MIDDLE: 62.5

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: 0.49
TOTAL INPUT: 100.49

OUTPUT IN KG

SPENT SHALE: 89.60
EXHAUST GAS: 0.
ANALYZER INTAKE: 6.52
OIL PRODUCED: 6.04
WATER FORMED: 2.99
TOTAL OUTPUT: 105.15
% UNACCOUNTED: -4.64

BOTTOM RECYCLE GAS, KG: 55.23
MIDDLE RECYCLE GAS, KG: 92.20

GAS ANALYSIS IN MOL %

H2: 5.19
N2: 79.92
O2: 1.20
CO2: 5.40
CO: 4.19
CH4: 0.99
C2: 1.52
C3: 1.530
C4: 0.060

BTU PER SCFM: 111.64

DISTRIBUTION OF ORGANIC CARBON
% OIL 45.34
% SPENT SHALE: 40.20
% GAS: 3.69

% UNACCOUNTED CARBON: 10.76

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 49.10
GAS: 4.10
SPENT SHALE: 21.76

YIELD, % OF F.A: 68.30

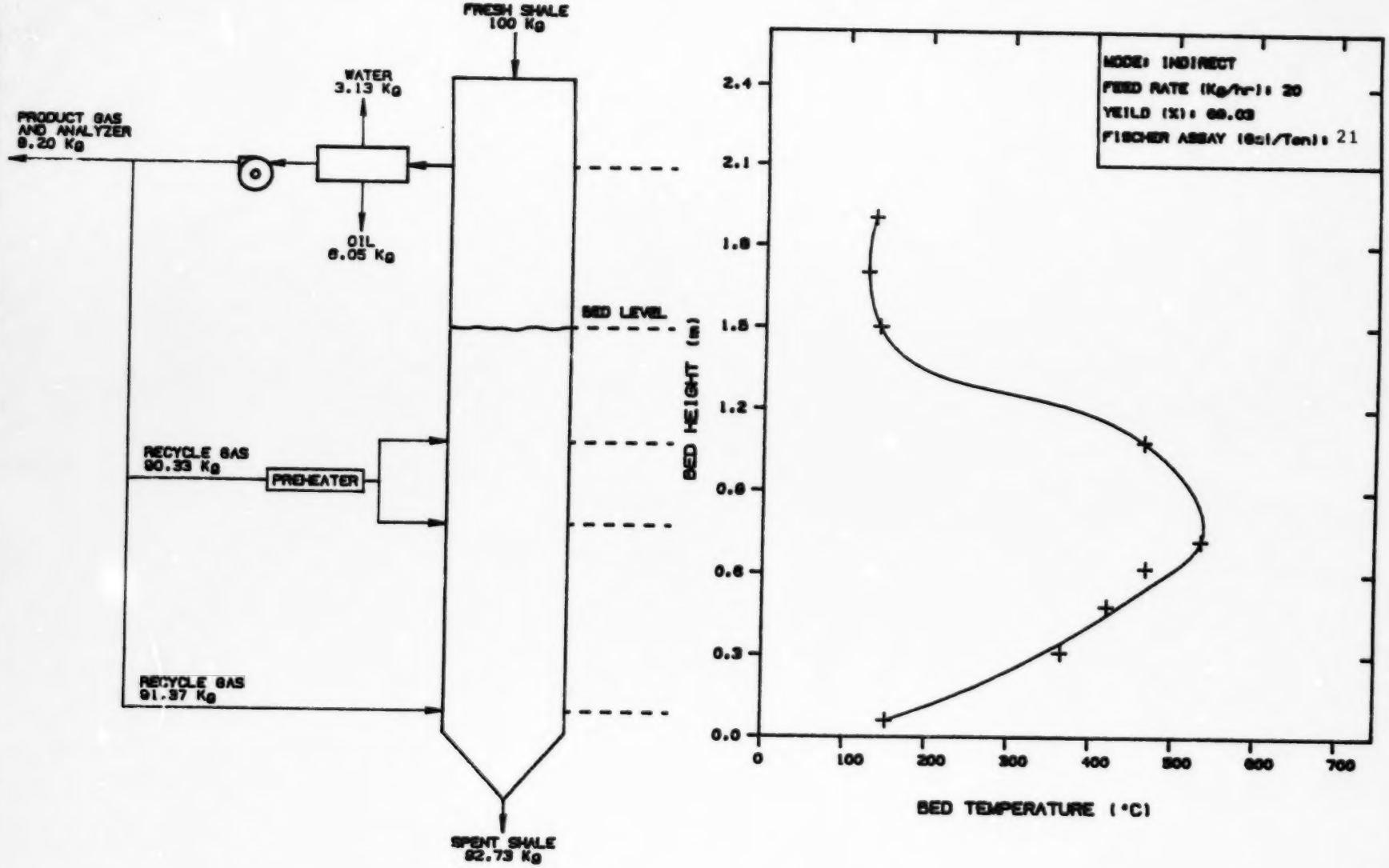


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 15

EXPERIMENT NO:18 SHALE NO: 1

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.48
FEED RATE, KG/HR: 20.00
DURATION, HR: 13.00
RESIDENCE TIME IN HR: 3.91
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.82
RECYCLE GAS SPLIT, %: BOTTOM: 50.3 MIDDLE: 49.7

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: 3.93
TOTAL INPUT: 103.93

OUTPUT IN KG

SPENT SHALE: 92.69
EXHAUST GAS: 0.
ANALYZER INTAKE: 8.20
OIL PRODUCED: 6.05
WATER FORMED: 3.13
TOTAL OUTPUT: 110.08
% UNACCOUNTED: -5.92

BOTTOM RECYCLE GAS, KG: 91.37
MIDDLE RECYCLE GAS, KG: 90.33

GAS ANALYSIS IN MOL %

H2: 4.40
N2: 80.08
O2: 1.40
CO2: 5.60
CO: 4.60
CH4: 1.19
C2: 1.37
C3: 1.290
C4: 0.070

BTU PER SCFM: 103.82

DISTRIBUTION OF ORGANIC CARBON
% OIL 43.91
% SPENT SHALE: 41.93
% GAS: 4.76

% UNACCOUNTED CARBON: 9.39

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 47.95
GAS: 4.67
SPENT SHALE: 22.49

YIELD, % OF F.A: 69.03

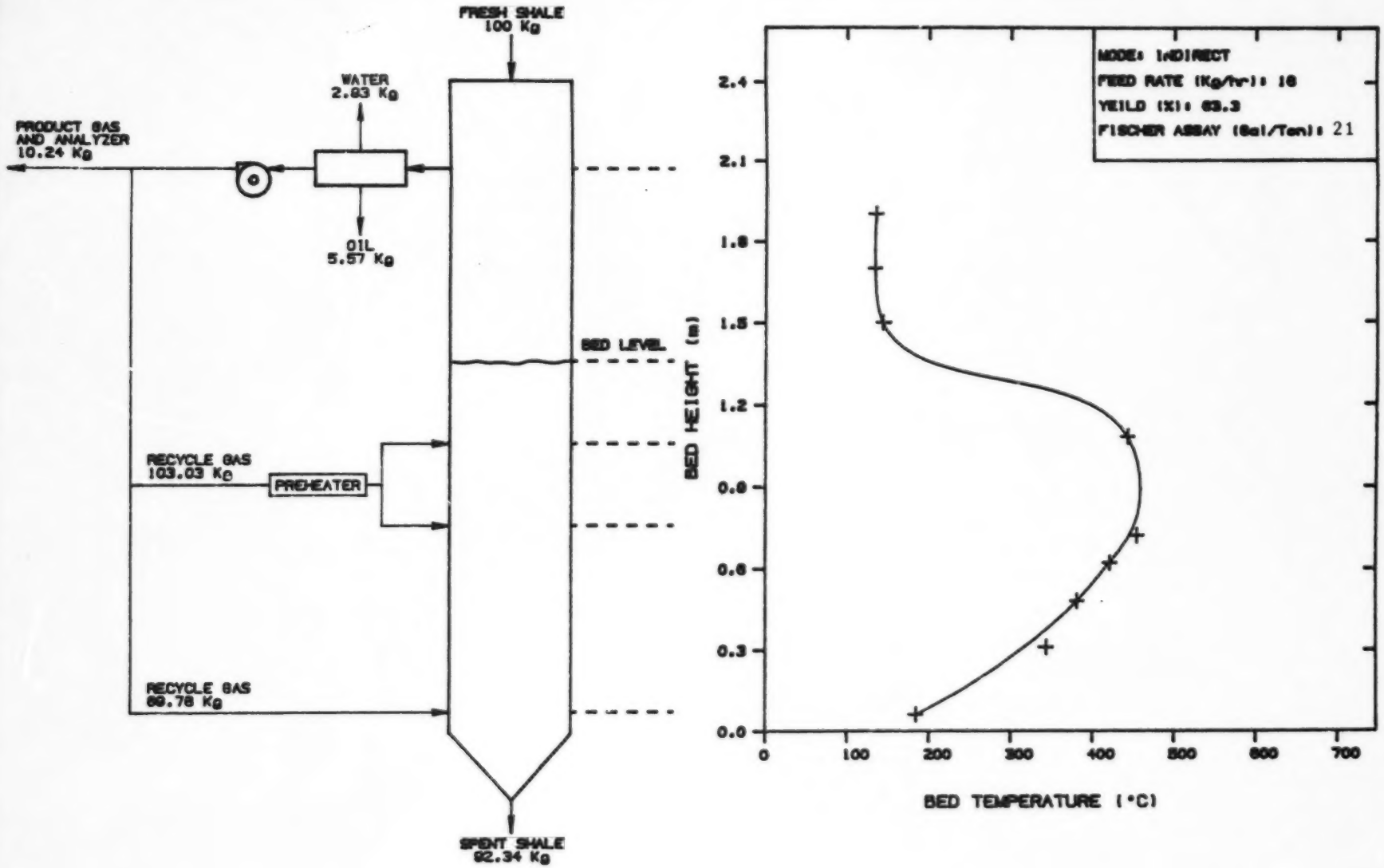


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 16

EXPERIMENT NO:16 SHALE NO: 1

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.36
FEED RATE, KG/HR: 16.00
DURATION, HR: 14.00
RESIDENCE TIME IN HR: 4.50
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.73
RECYCLE GAS SPLIT, %: BOTTOM: 40.4 MIDDLE: 59.6

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: 5.21
TOTAL INPUT: 105.21

OUTPUT IN KG

SPENT SHALE: 96.34
EXHAUST GAS: 0.
ANALYZER INTAKE: 10.24
OIL PRODUCED: 5.57
WATER FORMED: 2.93
TOTAL OUTPUT: 115.08
% UNACCOUNTED: -9.37

BOTTOM RECYCLE GAS, KG: 69.78
MIDDLE RECYCLE GAS, KG: 103.03

GAS ANALYSIS IN MOL %

H2: 4.10
N2: 80.22
O2: 1.14
CO2: 5.45
CO: 5.45
CH4: 1.43
C2: 1.23
C3: 0.930
C4: 0.050

BTU PER SCFM: 95.54

DISTRIBUTION OF ORGANIC CARBON
% OIL 39.98
% SPENT SHALE: 44.82
% GAS: 5.57

% UNACCOUNTED CARBON: 9.67

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 42.63
GAS: 5.16
SPENT SHALE: 25.62

YIELD, % OF F.A: 63.30

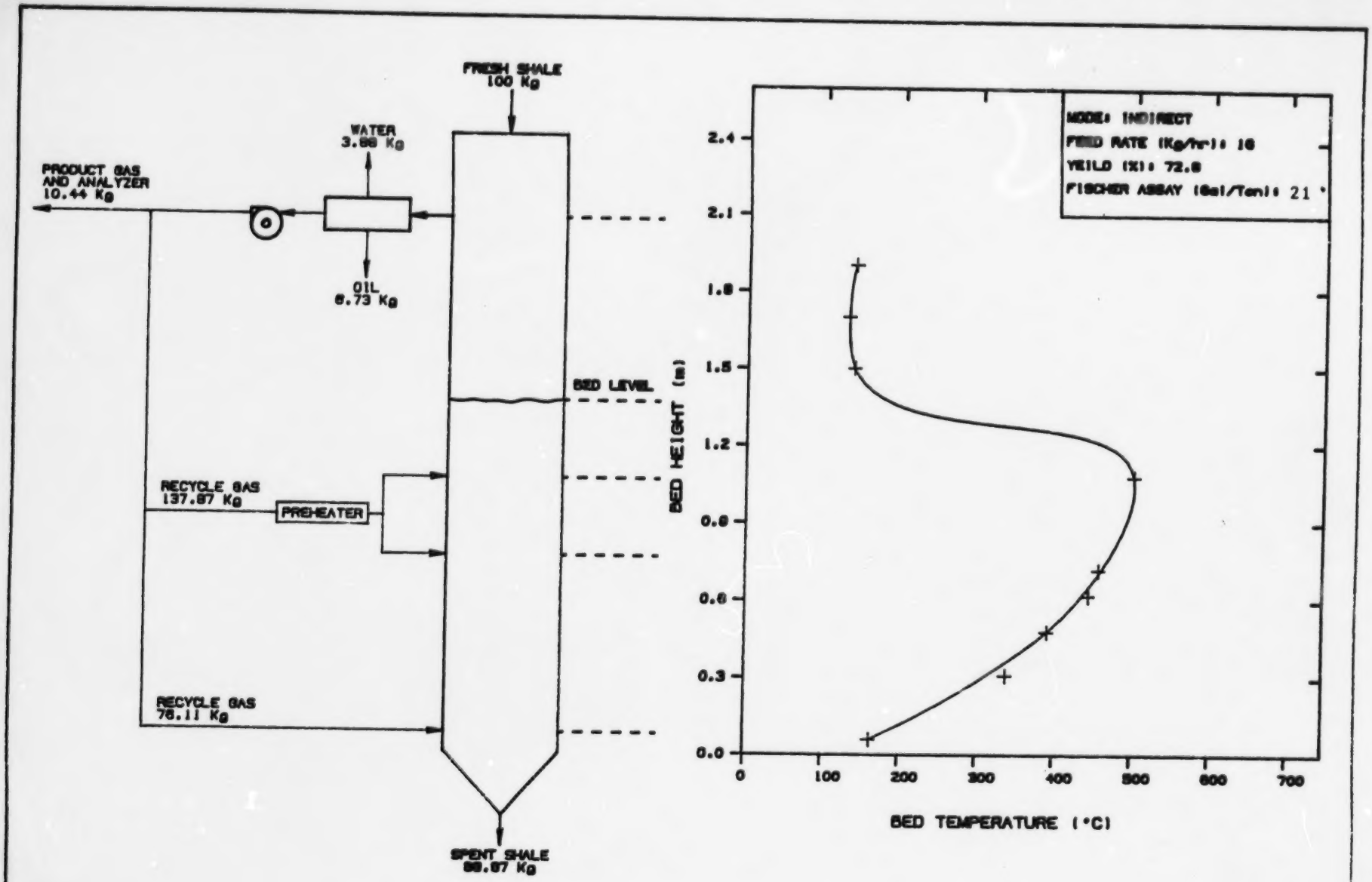


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 17

EXPERIMENT NO:17 SHALE NO: 1

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.43
FEED RATE, KG/HR: 16.00
DURATION, HR: 16.00
RESIDENCE TIME IN HR: 4.73
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.14
RECYCLE GAS SPLIT, %: BOTTOM: 35.6 MIDDLE: 64.4

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: 0.57
TOTAL INPUT: 100.57

OUTPUT IN KG

SPENT SHALE: 88.87
EXHAUST GAS: 0.
ANALYZER INTAKE: 10.44
OIL PRODUCED: 6.73
WATER FORMED: 3.88
TOTAL OUTPUT: 109.91
% UNACCOUNTED: -9.29

BOTTOM RECYCLE GAS, KG: 76.11
MIDDLE RECYCLE GAS, KG: 137.87

GAS ANALYSIS IN MOL %

H2: 3.11
N2: 81.52
O2: 1.50
CO2: 6.61
CO: 3.35
CH4: 1.11
C2: 1.48
C3: 1.270
C4: 0.050

BTU PER SCFM: 95.00

DISTRIBUTION OF ORGANIC CARBON
% OIL 50.46
% SPENT SHALE: 36.12
% GAS: 6.57

% UNACCUUNTED CARBON: 6.85

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 51.13
GAS: 5.11
SPENT SHALE: 19.40

YIELD, % OF F.A: 72.80

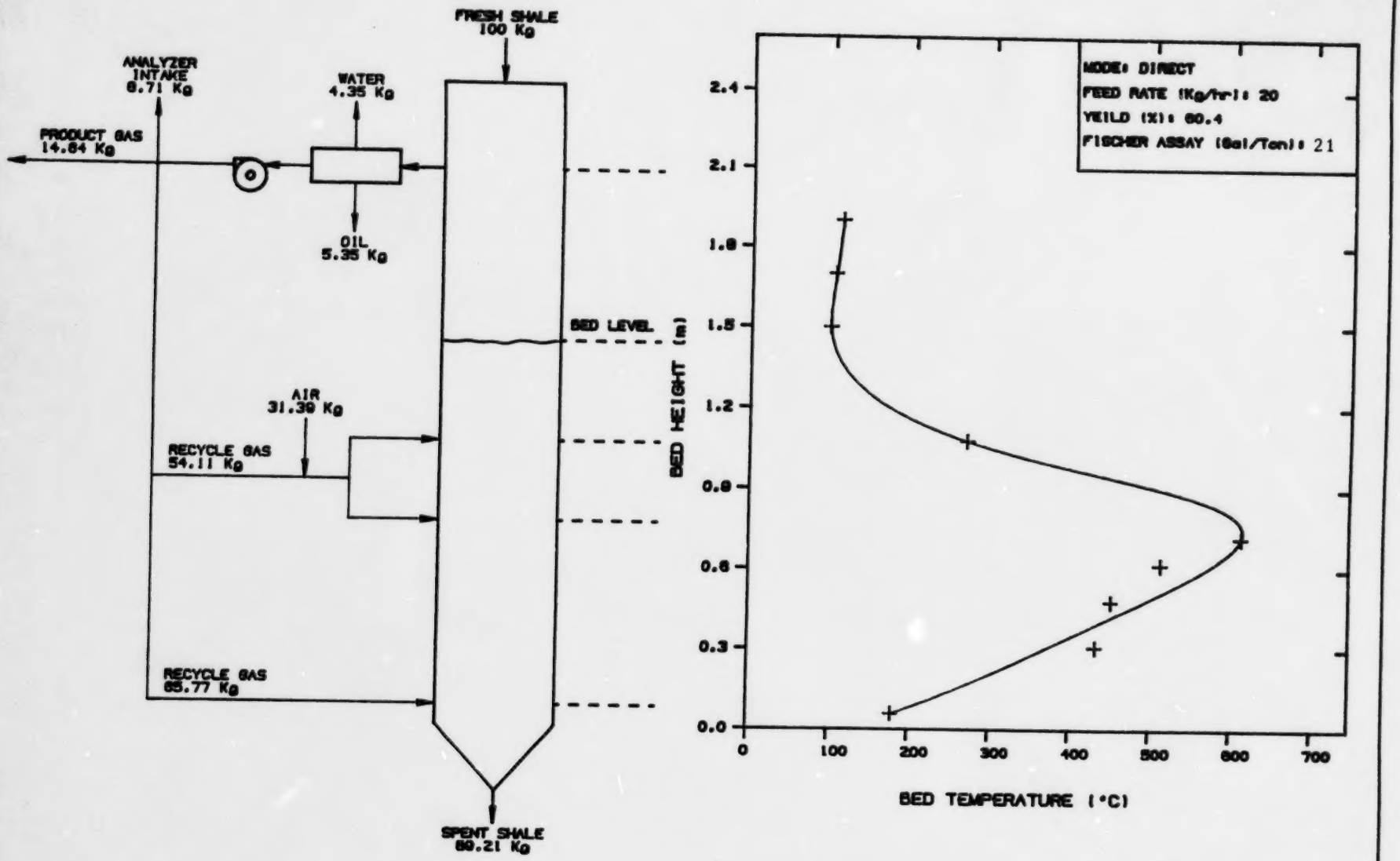


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 18

EXPERIMENT NO:18 SHALE NO: 1

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.43
FEED RATE, KG/HR: 20.00
DURATION, HR: 13.00
RESIDENCE TIME IN HR: 3.78
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.17
RECYCLE GAS SPLIT, % : BOTTOM: 54.9 MIDDLE: 45.1

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 31.39
AIR BOTTOM: 0.
ACCUM/DEPLE: -0.56
TOTAL INPUT: 130.82

OUTPUT IN KG

SPENT SHALE: 89.21
EXHAUST GAS: 14.31
ANALYZER INTAKE: 8.71
OIL PRODUCED: 5.35
WATER FORMED: 4.35
TOTAL OUTPUT: 121.92
% UNACCOUNTED: 6.81

BOTTOM RECYCLE GAS, KG: 64.28
MIDDLE RECYCLE GAS, KG: 52.89

GAS ANALYSIS IN MOL %

N2: 1.50
N2: 79.44
O2: 0.94
CO2: 10.92

CO: 4.64
CH4: 0.52
C2: 0.39
C3: 1.580
C4: 0.070

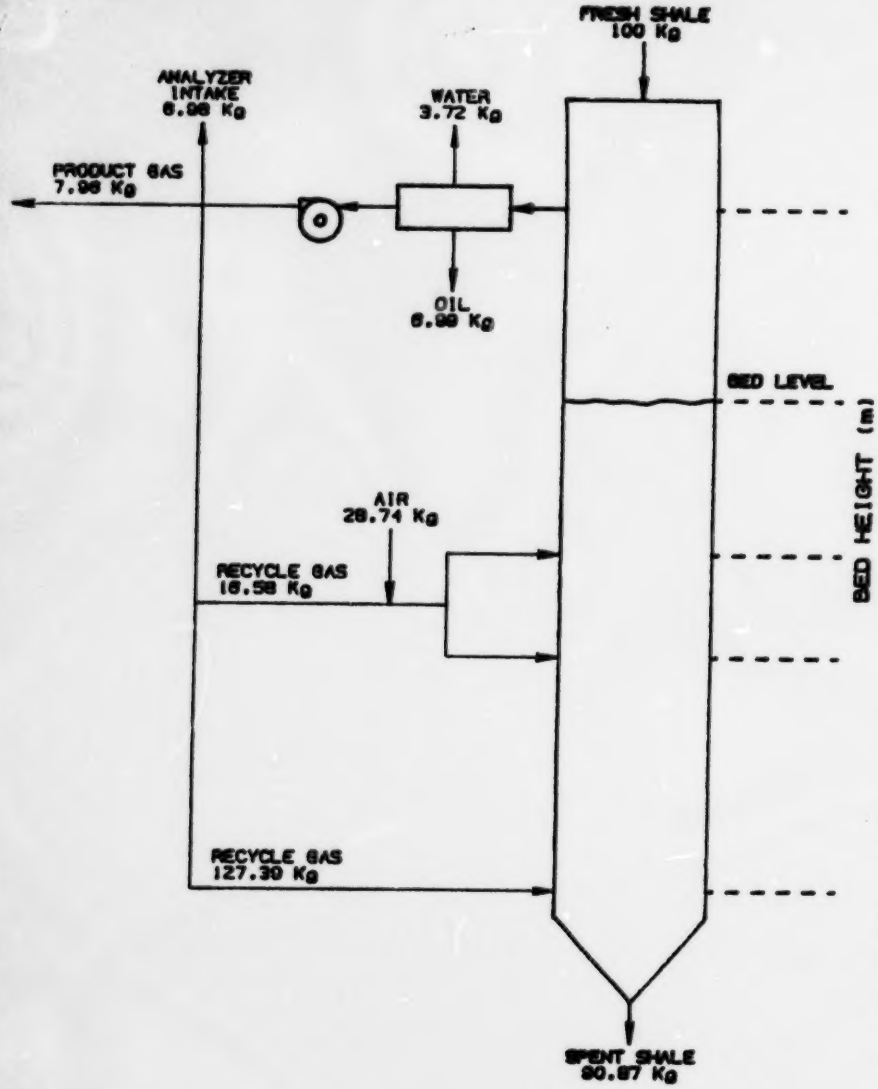
BTU PER SCFM: 77.53

DISTRIBUTION OF CARBON
% OIL 40.59
% SPENT SHALE: 44.86
% GAS: 9.96
% UNACCOUNTED CARBON: 4.59

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 49.64
GAS: 10.85
SPENT SHALE: 26.40

YIELD, % OF F.A: 60.40



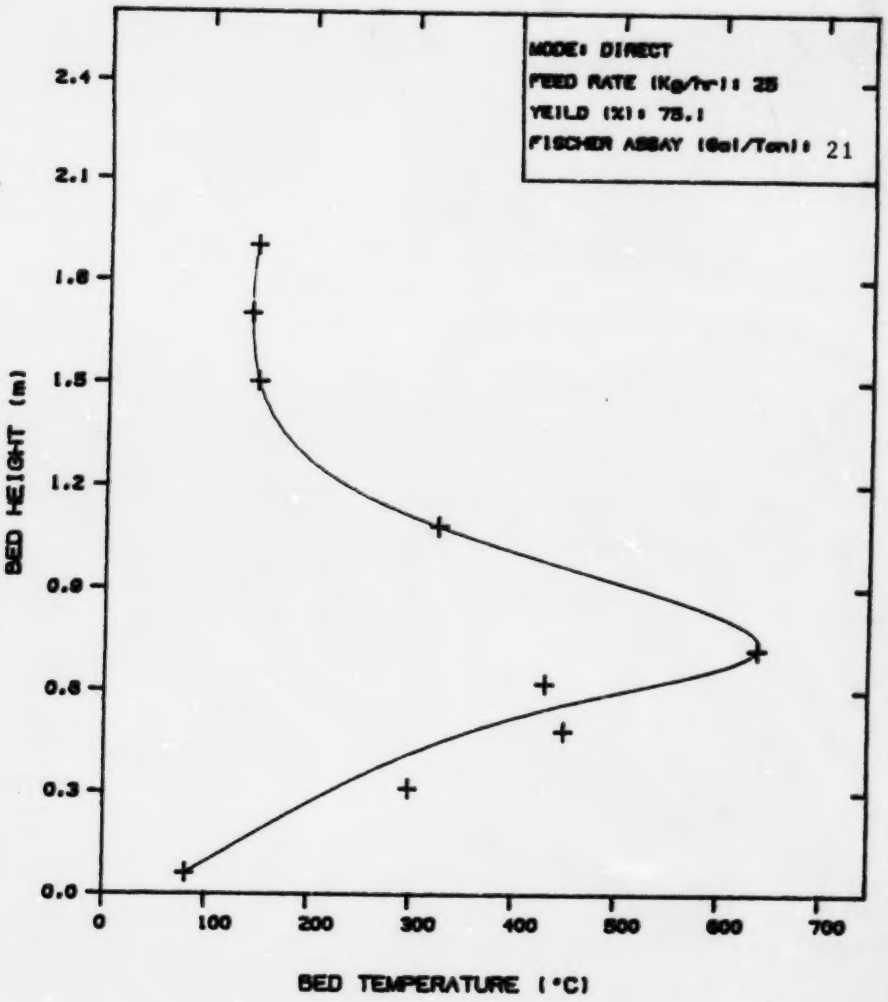


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 20

EXPERIMENT NO:20 SHALE NO: 1

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.51
FEED RATE, KG/HR: 25.00
DURATION, HR: 17.00
RESIDENCE TIME IN HR: 3.20
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.44
RECYCLE GAS SPLIT, % : BOTTOM: 88.5 MIDDLE: 11.5

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 28.74
AIR BOTTOM: 0.
ACCUM/DEPLE: 1.72
TOTAL INPUT: 130.46

OUTPUT IN KG

SPENT SHALE: 90.87
EXHAUST GAS: 7.96
ANALYZER INTAKE: 6.98
OIL PRODUCED: 6.99
WATER FORMED: 3.72
TOTAL OUTPUT: 116.52
% UNACCOUNTED: 10.69

BOTTOM RECYCLE GAS, KG: 127.39
MIDDLE RECYCLE GAS, KG: 16.58

GAS ANALYSIS IN MOL %

H2: 1.90
N2: 75.68
O2: 0.
CO2: 11.80
CO: 7.81
CH4: 0.39
C2: 0.43
C3: 1.890
C4: 0.100

BTU PER SCFM: 98.22

DISTRIBUTION OF CARBON
% OIL 51.83
% SPENT SHALE: 40.83
% GAS: 8.19
% UNACCOUNTED CARBON: -0.84

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 63.39
GAS: 8.71
SPENT SHALE: 24.98

YIELD, % OF F.A: 75.10

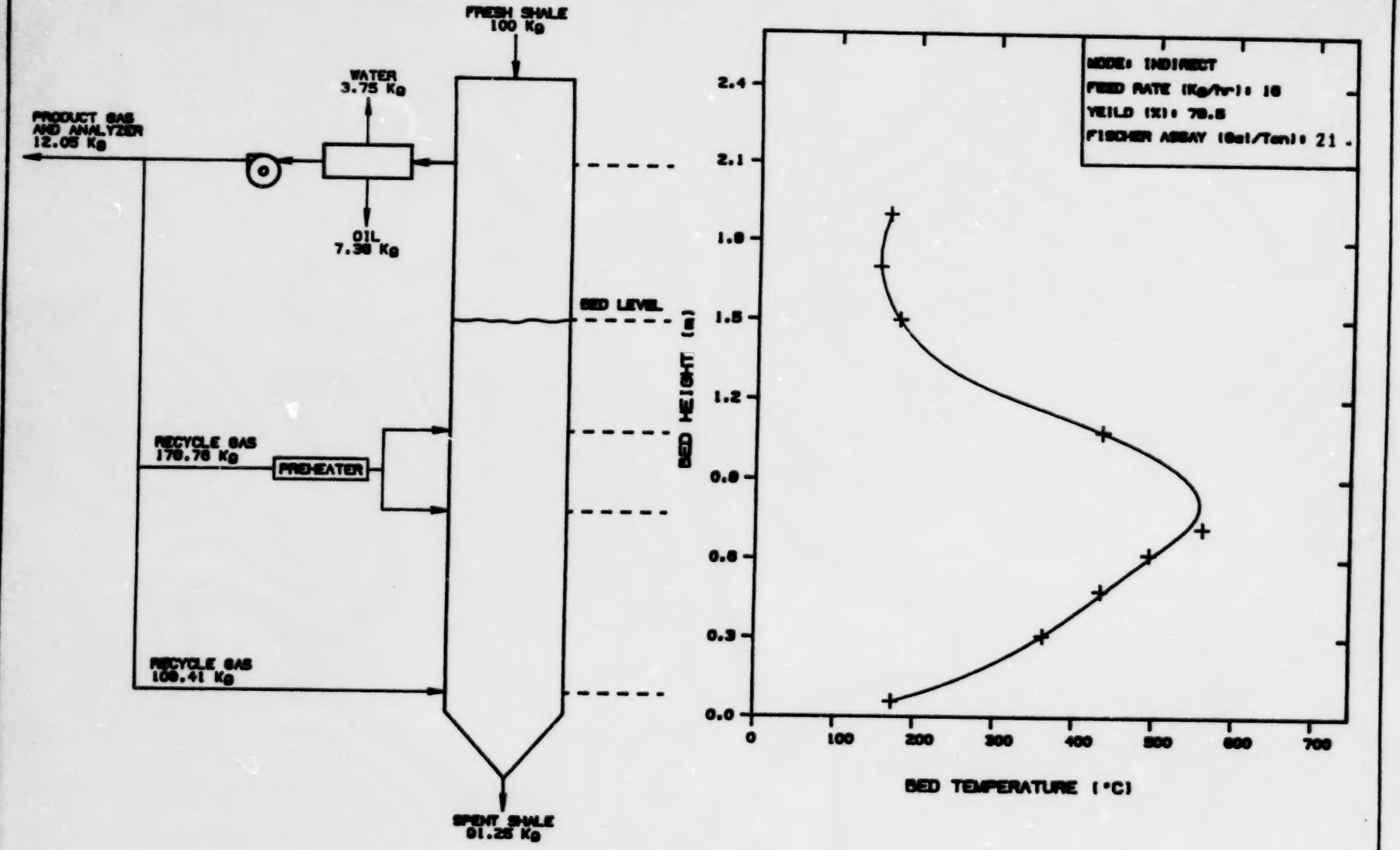


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 21

EXPERIMENT NO:21 SHALE NO: 1

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.48
FEED RATE, KG/HR: 16.00
DURATION, HR: 14.00
RESIDENCE TIME IN HR: 4.89
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.86
RECYCLE GAS SPLIT, %: BOTTOM: 38.2 MIDDLE: 61.8

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: 0.
TOTAL INPUT: 100.00

OUTPUT IN KG

SPENT SHALE: 91.25
EXHAUST GAS: 0.
ANALYZER INTAKE: 12.05
OIL PRODUCED: 7.38
WATER FORMED: 3.75
TOTAL OUTPUT: 114.43
% UNACCOUNTED: -14.43

BOTTOM RECYCLE GAS, KG: 109.41
MIDDLE RECYCLE GAS, KG: 176.76

GAS ANALYSIS IN MOL %

H2: 1.76
N2: 82.92
O2: 1.49
CO2: 6.99
CO: 2.57
CH4: 1.83
C2: 2.24
C3: 0.180
C4: 0.050

BTU PER SCFM: 79.68

DISTRIBUTION OF ORGANIC CARBON
% OIL 55.64
% SPENT SHALE: 38.98
% GAS: 6.85

% UNACCOUNTED CARBON: -1.47

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 54.26
GAS: 4.80
SPENT SHALE: 19.94

YIELD, % OF F.A: 78.80

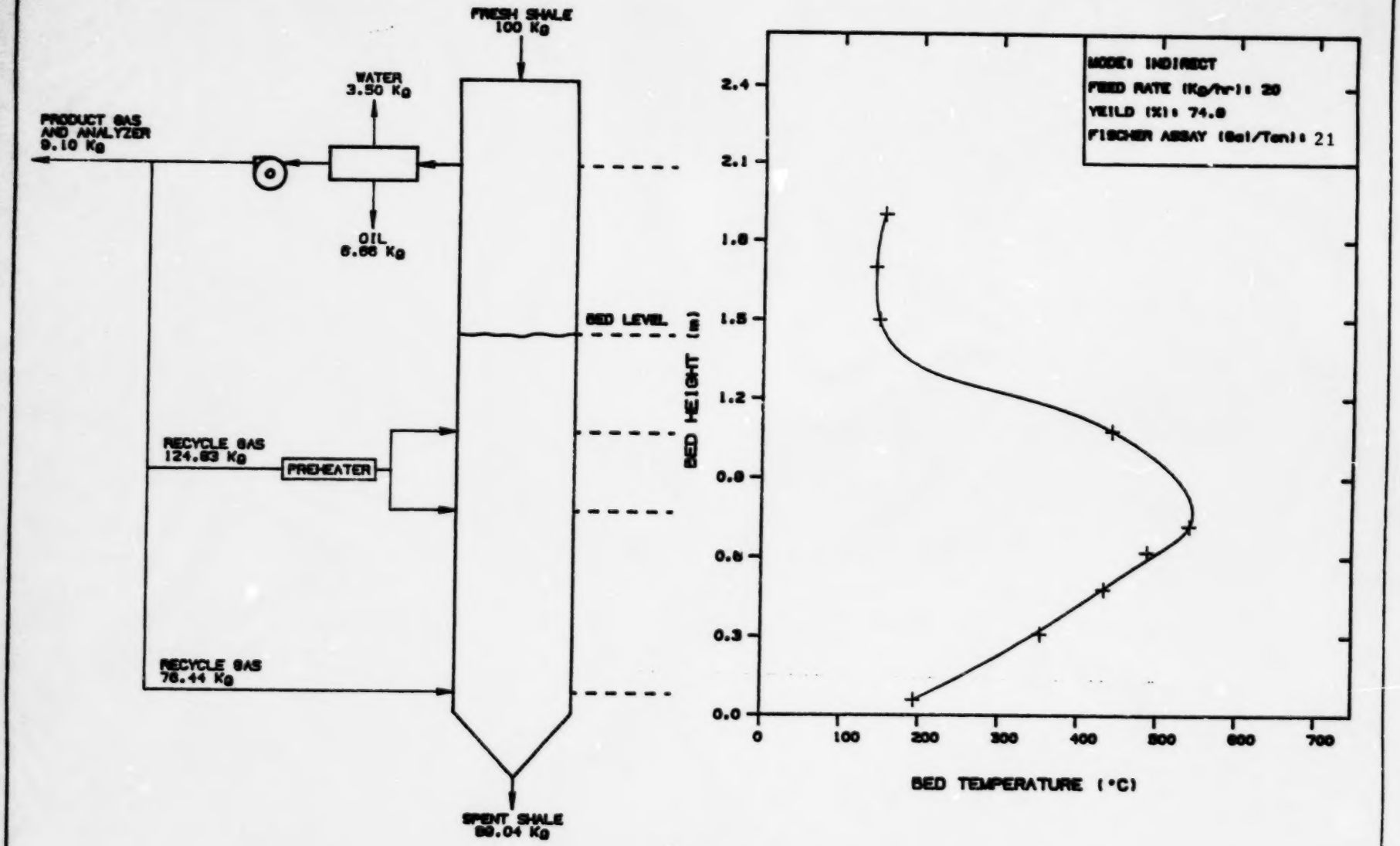


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 22

EXPERIMENT NO:22 SHALE NO: 1

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.43
FEED RATE, KG/HR: 20.00
DURATION, HR: 14.00
RESIDENCE TIME IN HR: 3.78
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.01
RECYCLE GAS SPLIT, %: BOTTOM: 38.0 MIDDLE: 62.0

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: -1.04
TOTAL INPUT: 98.96

OUTPUT IN KG

SPENT SHALE: 89.04
EXHAUST GAS: 0.
ANALYZER INTAKE: 9.10
OIL PRODUCED: 6.66
WATER FORMED: 3.50
TOTAL OUTPUT: 108.30
% UNACCOUNTED: -9.44

BOTTOM RECYCLE GAS, KG: 76.44
MIDDLE RECYCLE GAS, KG: 124.83

GAS ANALYSIS IN MOL %

H2: 4.00
N2: 80.72
O2: 1.31
CO2: 6.03
CO: 3.40
CH4: 1.70
C2: 2.49
C3: 0.280
C4: 0.070

BTU PER SCFM: 96.49

DISTRIBUTION OF ORGANIC CARBON
% OIL 50.78
% SPENT SHALE: 38.91
% GAS: 5.38

% UNACCOUNTED CARBON: 4.93

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 52.39
GAS: 4.82
SPENT SHALE: 20.76

YIELD, % OF F.A: 74.90

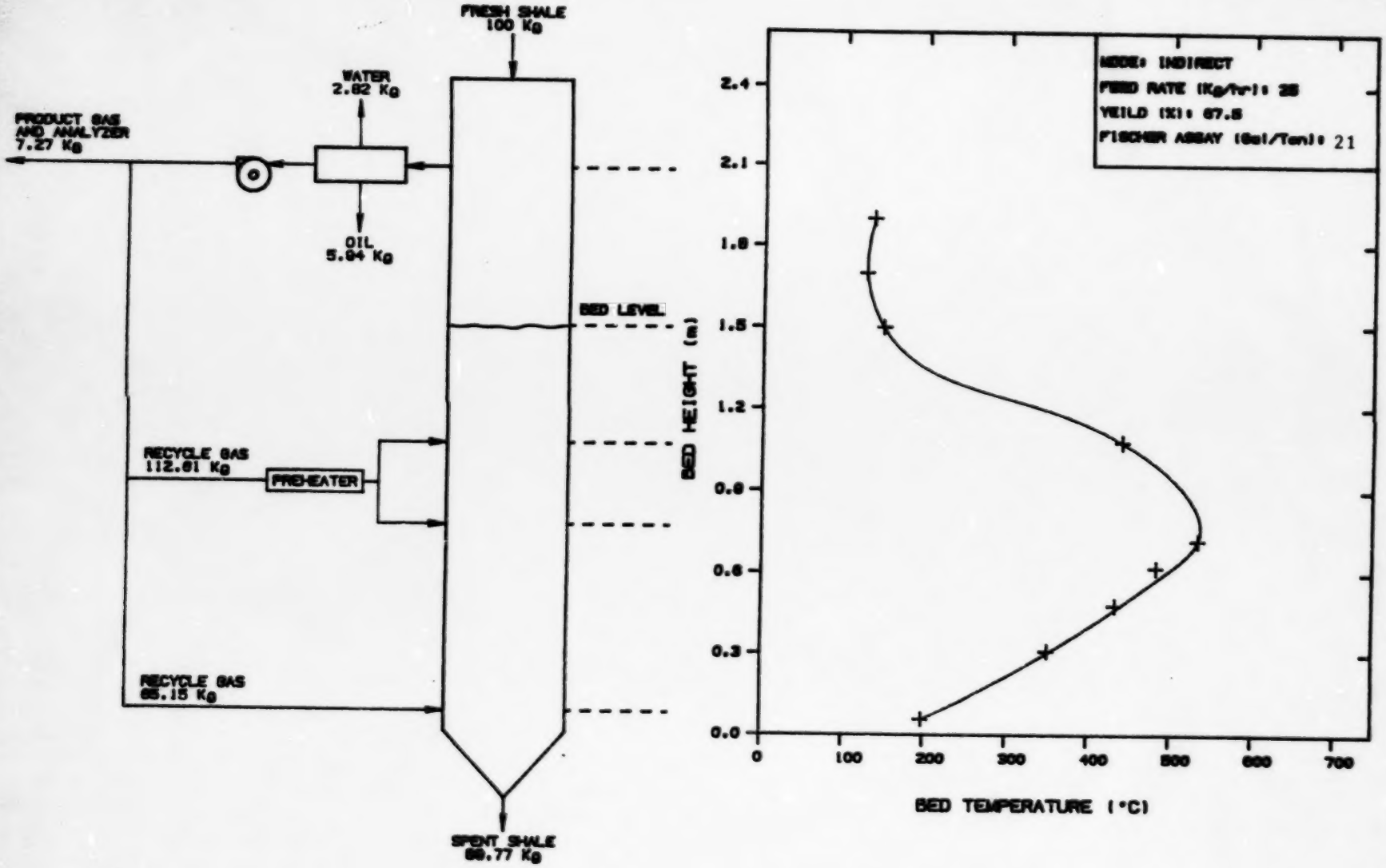


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 23

EXPERIMENT NO:23 SHALE NO: 1

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.49
FEED RATE, KG/HR: 25.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 3.15
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.78
RECYCLE GAS SPLIT, %: BOTTOM: 36.7 MIDDLE: 63.3

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: 0.49
TOTAL INPUT: 100.49

OUTPUT IN KG

SPENT SHALE: 89.77
EXHAUST GAS: 0.
ANALYZER INTAKE: 7.27
OIL PRODUCED: 5.94
WATER FORMED: 2.82
TOTAL OUTPUT: 105.79
% UNACCOUNTED: -5.28

BOTTOM RECYCLE GAS, KG: 65.15
MIDDLE RECYCLE GAS, KG: 112.61

GAS ANALYSIS IN MOL %

H2: 4.10
N2: 81.17
O2: 1.31
CO2: 5.48
CO: 3.61
CH4: 1.34
C2: 2.37
C3: 0.600
C4: 0.120

BTU PER SCFM: 99.20

DISTRIBUTION OF ORGANIC CARBON
% OIL 44.67
% SPENT SHALE: 44.59
% GAS: 3.98

% UNACCOUNTED CARBON: 6.86

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 46.99
GAS: 3.96
SPENT SHALE: 22.93

YIELD, % OF F.A: 67.80

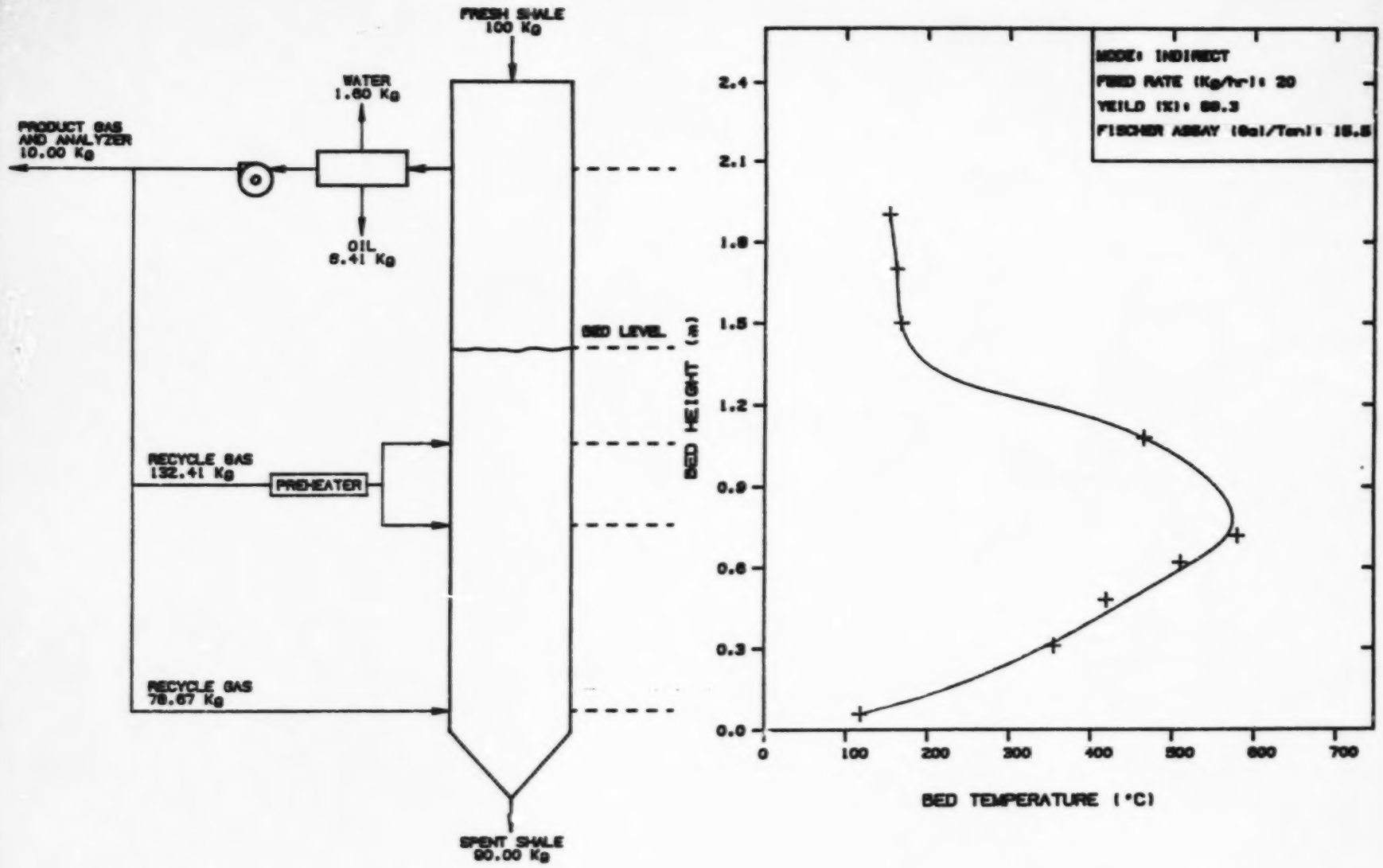


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 27

EXPERIMENT NO:27 SHALE NO: 2

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.41
FEED RATE, KG/HR: 20.00
DURATION, HR: 14.00
RESIDENCE TIME IN HR: 3.73
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.11
RECYCLE GAS SPLIT, %: BOTTOM: 37.3 MIDDLE: 62.7

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: 0.52
TOTAL INPUT: 100.52

OUTPUT IN KG

SPENT SHALE: 90.00
EXHAUST GAS: 0.
ANALYZER INTAKE: 10.00
OIL PRODUCED: 6.41
WATER FORMED: 1.60
TOTAL OUTPUT: 108.02
% UNACCOUNTED: -7.46

BOTTOM RECYCLE GAS, KG: 78.67
MIDDLE RECYCLE GAS, KG: 132.41

GAS ANALYSIS IN MOL %

H2: 4.09
N2: 77.29
O2: 1.57
CO2: 9.52
CO: 2.85
CH4: 1.67
C2: 2.52
C3: 0.380
C4: 0.110

BTU PER SCFM: 99.18

DISTRIBUTION OF ORGANIC CARBON
% OIL 55.15
% SPENT SHALE: 42.56
% GAS: 8.37

% UNACCOUNTED CARBON: -6.09

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 55.79
GAS: 5.95
SPENT SHALE: 24.38

YIELD, % OF F.A: 89.30

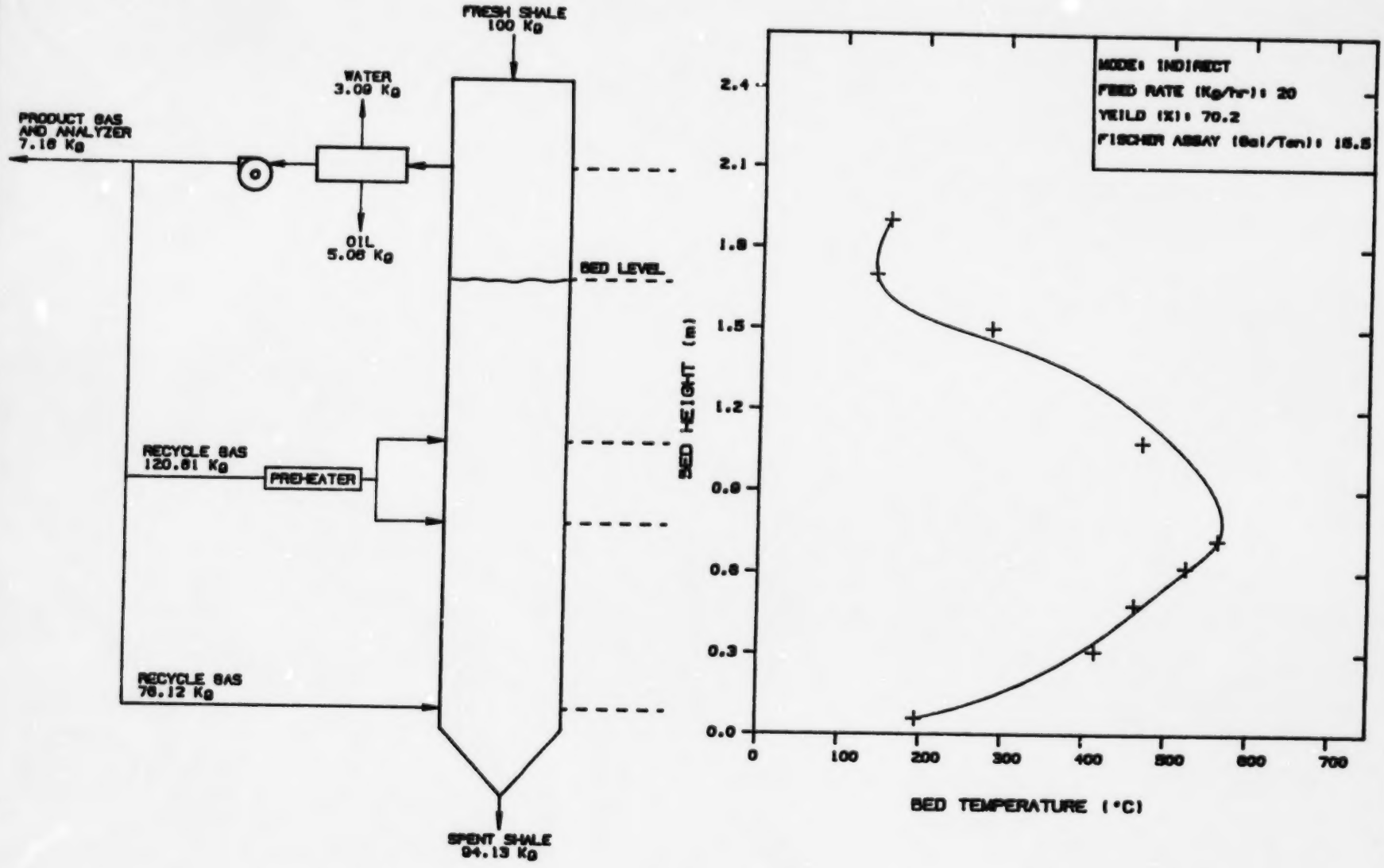


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 28

EXPERIMENT NO:28 SHALE NO: 2

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.53
FEED RATE, KG/HR: 20.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 4.05
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.97
RECYCLE GAS SPLIT, %: BOTTOM: 38.7 MIDDLE: 61.3

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: -2.43
TOTAL INPUT: 97.57

OUTPUT IN KG

SPENT SHALE: 94.13
EXHAUST GAS: 0.
ANALYZER INTAKE: 7.16
OIL PRODUCED: 5.06
WATER FORMED: 3.09
TOTAL OUTPUT: 109.43
% UNACCOUNTED: -12.16

BOTTOM RECYCLE GAS, KG: 76.12
MIDDLE RECYCLE GAS, KG: 120.61

GAS ANALYSIS IN MOL %

H2: 4.05
N2: 74.59
O2: 1.73
CO2: 9.30
CO: 3.20
CH4: 5.24
C2: 1.50
C3: 0.290
C4: 0.100

BTU PER SCFM: 117.72

DISTRIBUTION OF ORGANIC CARBON
% OIL 44.85
% SPENT SHALE: 38.98
% GAS: 6.59

% UNACCOUNTED CARBON: 9.59

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 46.22
GAS: 5.35
SPENT SHALE: 24.67

YIELD, % OF F.A: 70.20

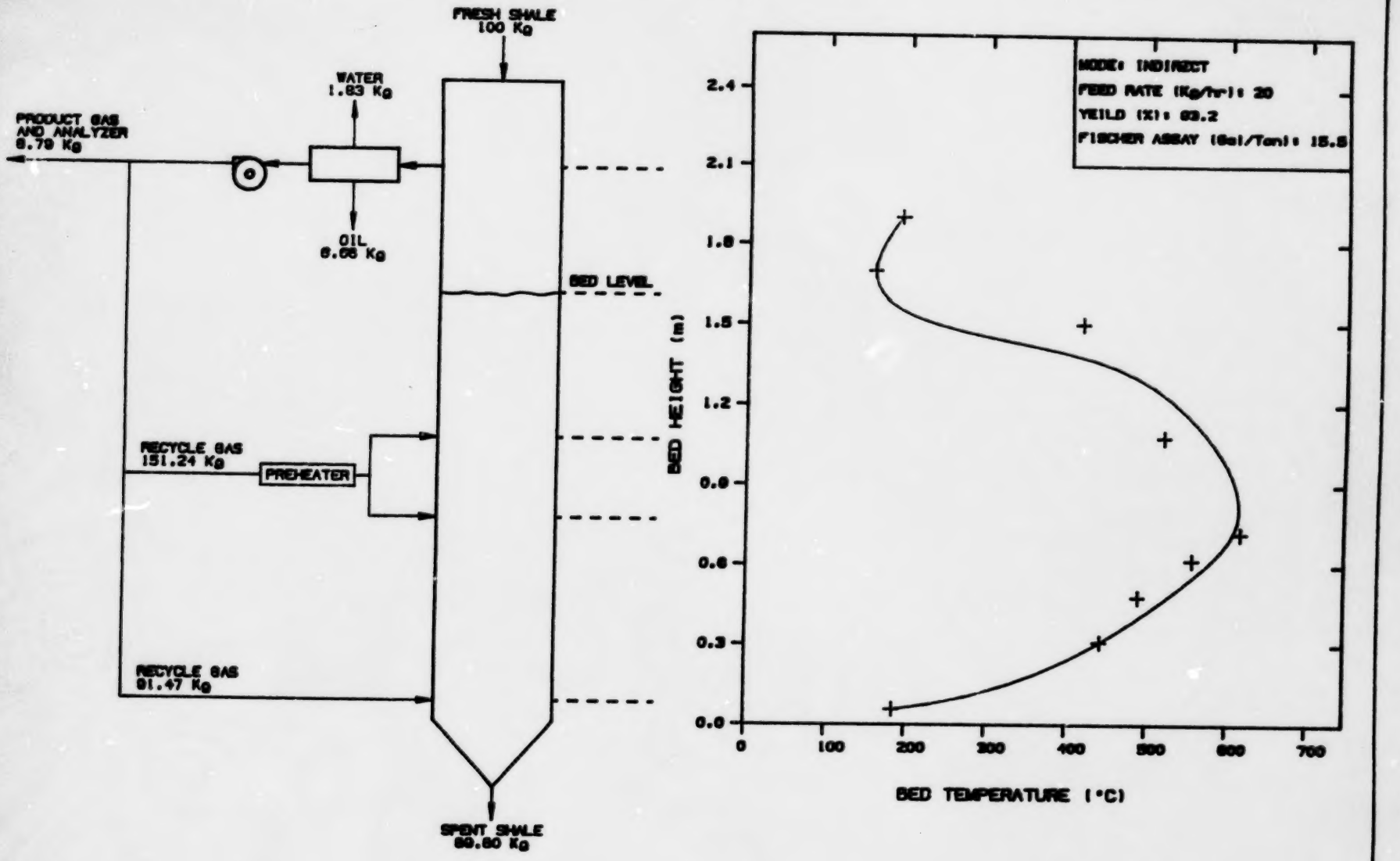


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 29

EXPERIMENT NO:29 SHALE NO: 2

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.60
FEED RATE, KG/HR: 20.00
DURATION, HR: 15.00
RESIDENCE TIME IN HR: 4.22
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.48
RECYCLE GAS SPLIT, %: BOTTOM: 37.7 MIDDLE: 62.3

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: -0.49
TOTAL INPUT: 99.51

OUTPUT IN KG

SPENT SHALE: 89.80
EXHAUST GAS: 0.
ANALYZER INTAKE: 8.79
OIL PRODUCED: 6.66
WATER FORMED: 1.83
TOTAL OUTPUT: 107.08
% UNACCOUNTED: -7.60

BOTTOM RECYCLE GAS, KG: 91.47
MIDDLE RECYCLE GAS, KG: 151.24

GAS ANALYSIS IN MOL %

H2: 4.00
N2: 76.29
O2: 2.07
CO2: 10.53
CO: 2.85
CH4: 2.03
C2: 1.88
C3: 0.180
C4: 0.170

BTU PER SCFM: 88.34

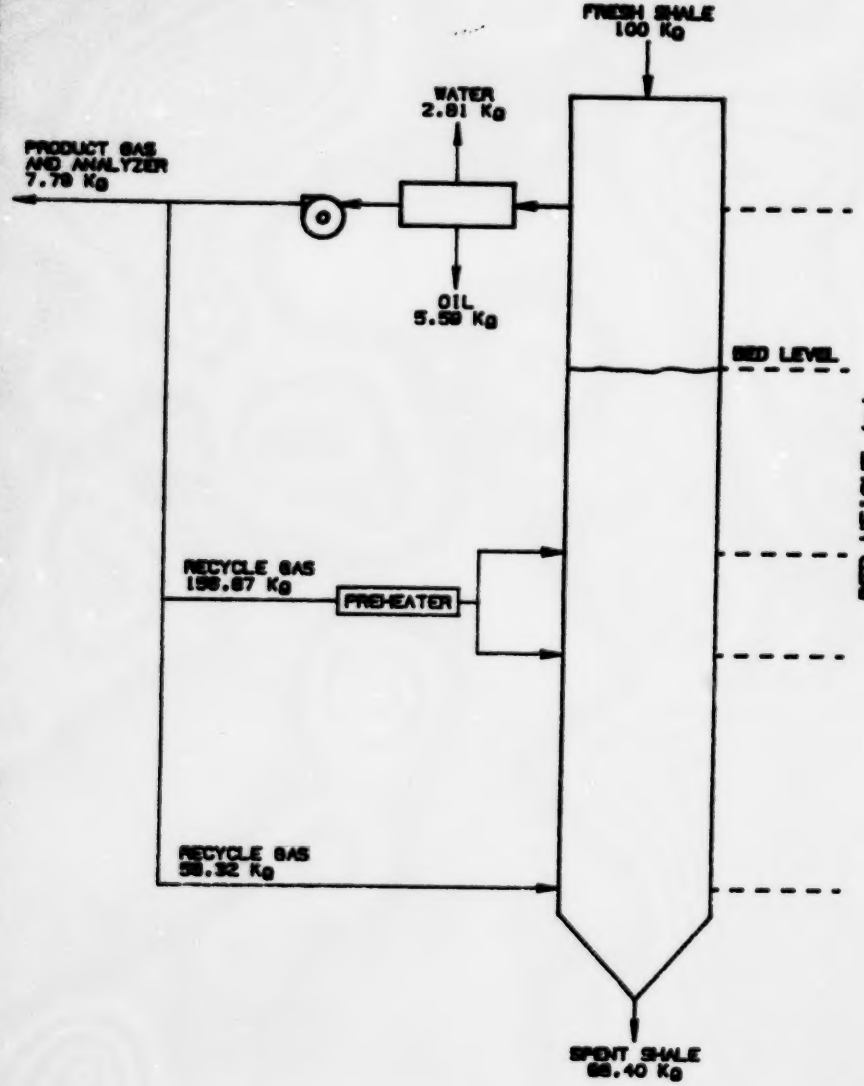
DISTRIBUTION OF ORGANIC CARBON
% OIL 57.87
% SPENT SHALE: 37.91
% GAS: 7.20

% UNACCOUNTED CARBON: -2.98

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 84.37
GAS: 4.58
SPENT SHALE: 22.77

YIELD, % OF F.A: 84.90



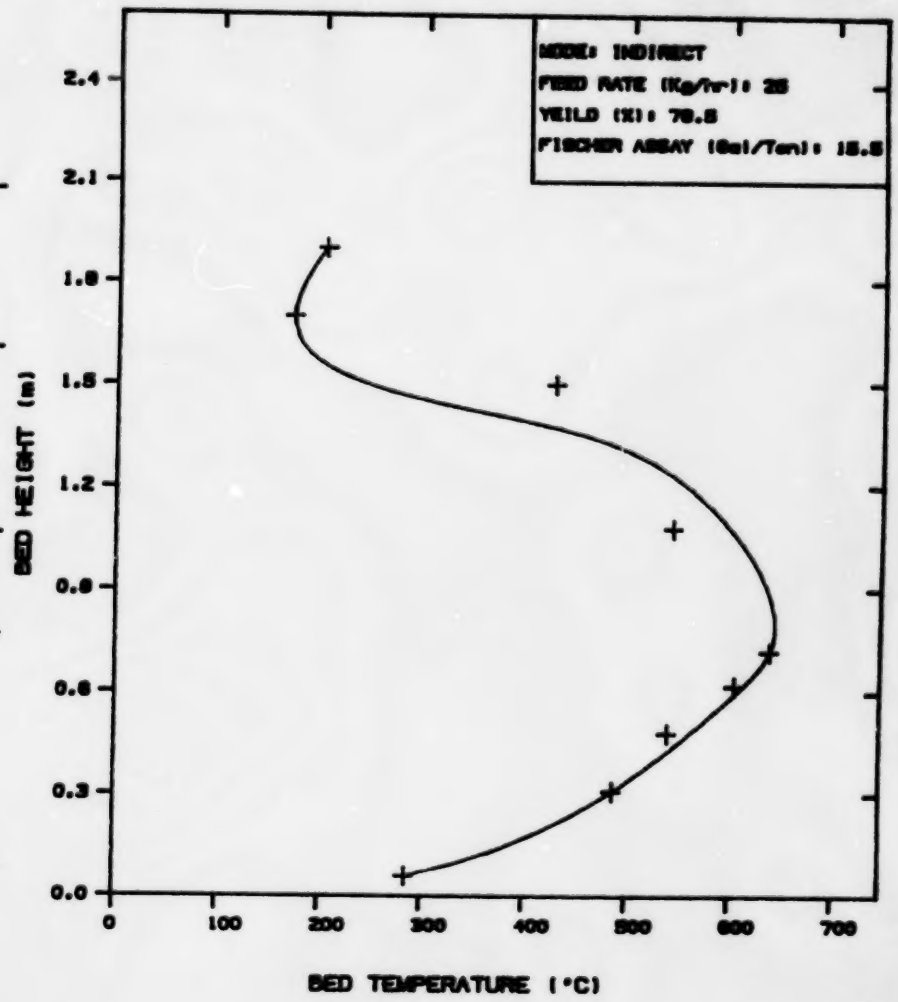


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 30

EXPERIMENT NO:30 SHALE NO: 2

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.61
FEED RATE, KG/HR: 25.00
DURATION, HR: 11.00
RESIDENCE TIME IN HR: 3.41
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.15
RECYCLE GAS SPLIT, %: BOTTOM: 27.1 MIDDLE: 72.9

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: -0.53
TOTAL INPUT: 99.47

OUTPUT IN KG

SPENT SHALE: 88.40
EXHAUST GAS: 0.
ANALYZER INTAKE: 7.80
OIL PRODUCED: 5.59
WATER FORMED: 2.81
TOTAL OUTPUT: 104.60
% UNACCOUNTED: -5.16

BOTTOM RECYCLE GAS, KG: 58.37
MIDDLE RECYCLE GAS, KG: 156.99

GAS ANALYSIS IN MOL %

H2: 2.76
N2: 75.86
O2: 2.39
CO2: 12.62
CO: 2.65
CH4: 1.77
C2: 1.90
C3: 0.260
C4: 0.090

BTU PER SCFM: 80.34

DISTRIBUTION OF ORGANIC CARBON
% OIL 48.57
% SPENT SHALE: 35.64
% GAS: 6.85

% UNACCOUNTED CARBON: 8.95

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 45.63
GAS: 3.58
SPENT SHALE: 21.81

YIELD, % OF F.A: 78.50

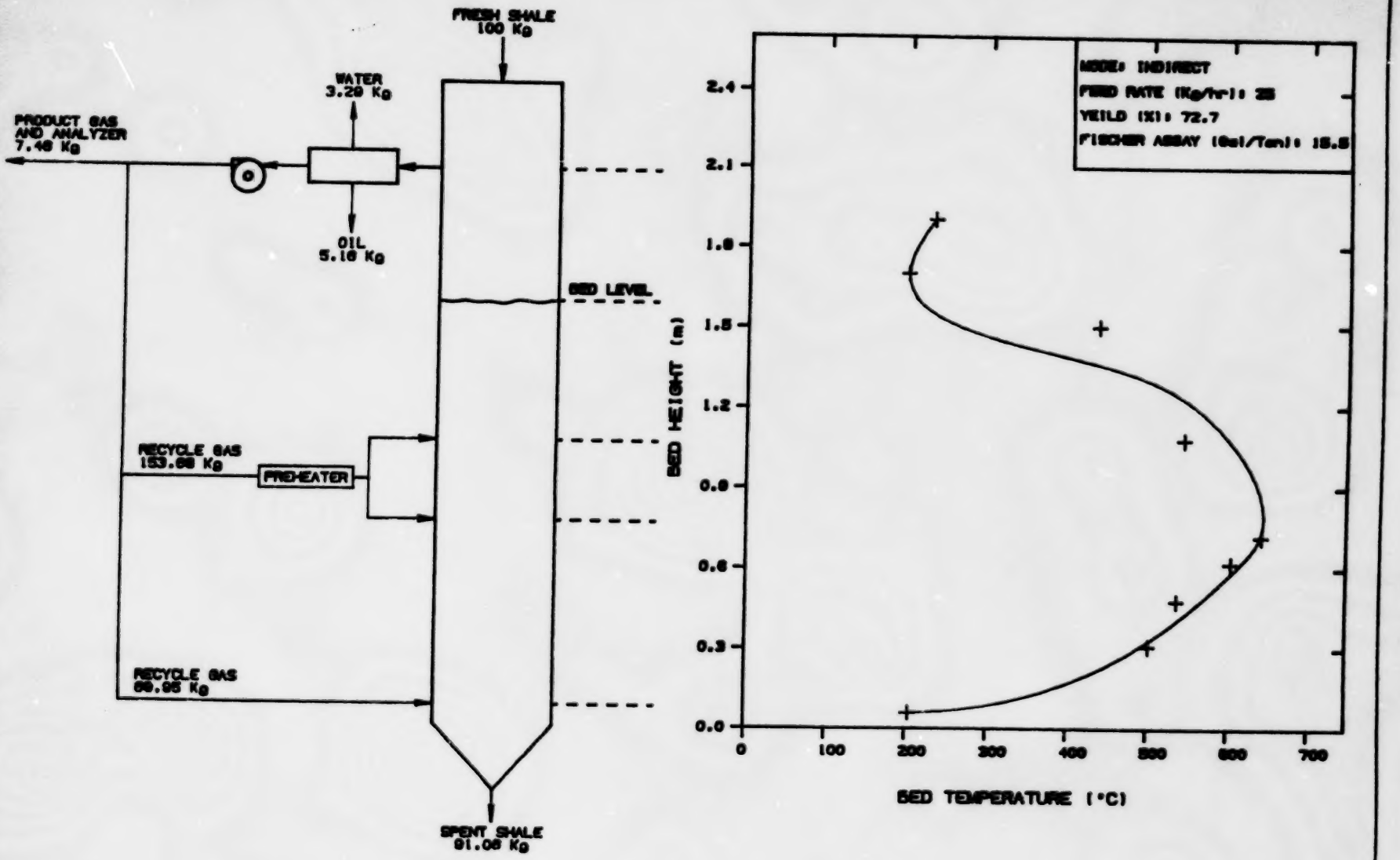


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 31

EXPERIMENT NO:31 SHALE NO: 2

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.58
FEED RATE, KG/HR: 25.00
DURATION, HR: 14.00
RESIDENCE TIME IN HR: 3.34
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.24
RECYCLE GAS SPLIT, %: BOTTOM: 31.3 MIDDLE: 68.7

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: -0.83
TOTAL INPUT: 99.17

OUTPUT IN KG

SPENT SHALE: 91.06
EXHAUST GAS: 0.
ANALYZER INTAKE: 7.46
OIL PRODUCED: 5.16
WATER FORMED: 3.29
TOTAL OUTPUT: 106.96
% UNACCOUNTED: -7.86

BOTTOM RECYCLE GAS, KG: 69.95
MIDDLE RECYCLE GAS, KG: 153.68

GAS ANALYSIS IN MOL %

H2: 4.00
N2: 75.56
O2: 3.60
CO2: 11.84
CO: 1.97
CH4: 1.55
C2: 1.42
C3: 0.190
C4: 0.080

BTU PER SCFM: 69.40

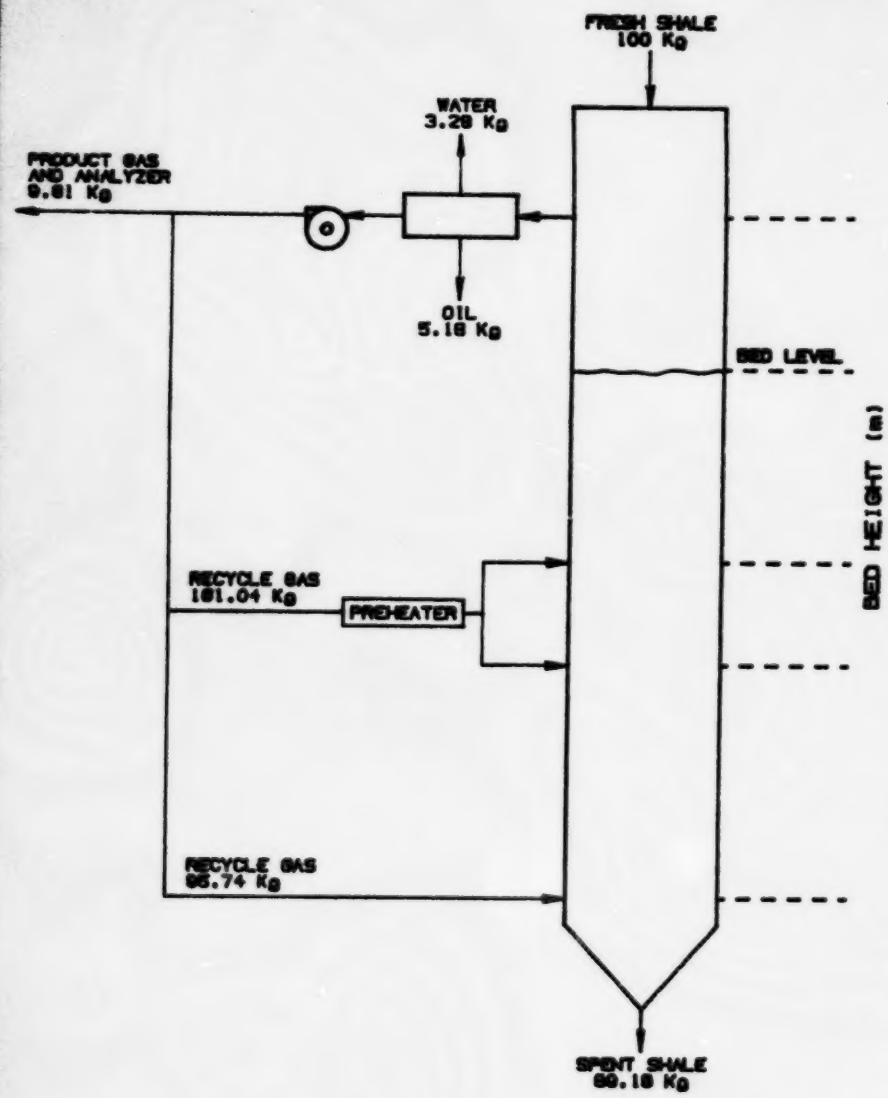
DISTRIBUTION OF ORGANIC CARBON
% OIL 44.95
% SPENT SHALE: 35.35
% GAS: 5.81

% UNACCOUNTED CARBON: 13.89

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 42.50
GAS: 3.01
SPENT SHALE: 22.02

YIELD, % OF F.A: 72.70



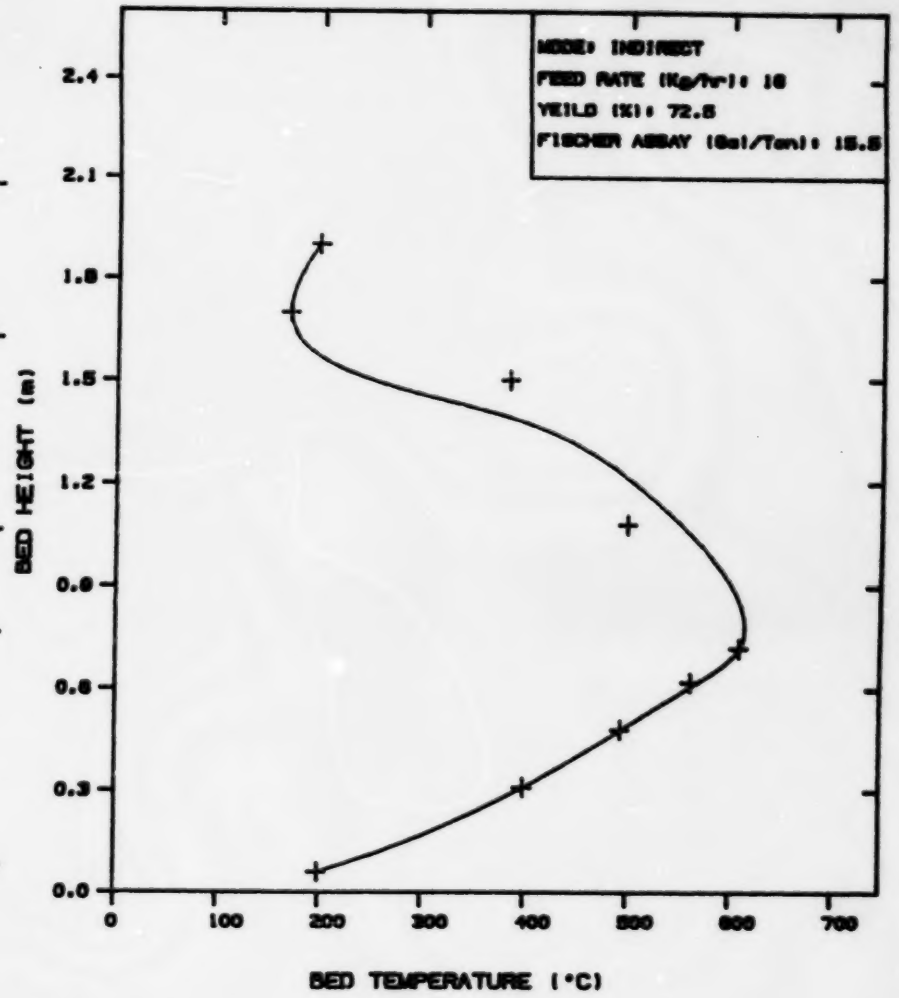


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 32

EXPERIMENT NO:32 SHALE NO: 2

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.62
FEED RATE, KG/HR: 16.00
DURATION, HR: 13.00
RESIDENCE TIME IN HR: 5.36
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.57
RECYCLE GAS SPLIT, %: BOTTOM: 37.3 MIDDLE: 62.7

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: 2.11
TOTAL INPUT: 102.11

OUTPUT IN KG

SPENT SHALE: 89.18
EXHAUST GAS: 0.
ANALYZER INTAKE: 9.81
OIL PRODUCED: 5.18
WATER FORMED: 3.28
TOTAL OUTPUT: 107.46
% UNACCOUNTED: -5.24

BOTTOM RECYCLE GAS, KG: 95.74
MIDDLE RECYCLE GAS, KG: 161.04

GAS ANALYSIS IN MOL %

H2: 2.50
N2: 77.14
O2: 2.49
CO2: 11.45
CO: 2.12
CH4: 2.23
C2: 1.72
C3: 0.170
C4: 0.110

BTU PER SCFM: 77.72

DISTRIBUTION OF ORGANIC CARBON
% OIL 43.87
% SPENT SHALE: 36.34
% GAS: 7.59

% UNACCOUNTED CARBON: 12.19

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 42.40
GAS: 4.30
SPENT SHALE: 21.98

YIELD, % OF F.A: 72.50

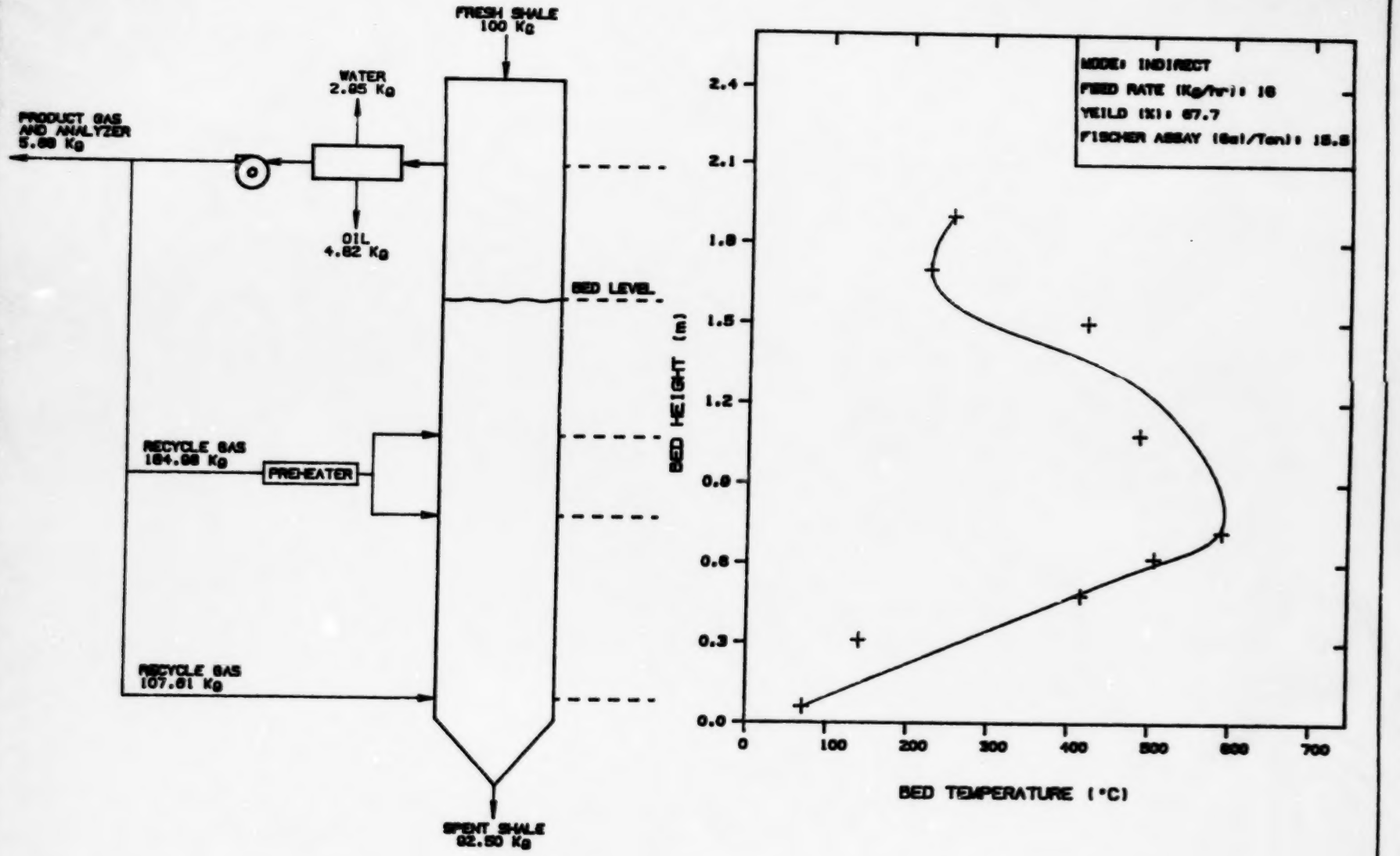


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 34

EXPERIMENT NO:34 SHALE NO: 2

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.57
FEED RATE, KG/HR: 16.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 5.19
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.93
RECYCLE GAS SPLIT, %: BOTTOM: 36.8 MIDDLE: 63.2

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: 3.04
TOTAL INPUT: 103.04

OUTPUT IN KG

SPENT SHALE: 92.50
EXHAUST GAS: 0.
ANALYZER INTAKE: 5.68
OIL PRODUCED: 4.82
WATER FORMED: 2.95
TOTAL OUTPUT: 105.95
% UNACCOUNTED: -2.82

BOTTOM RECYCLE GAS, KG: 107.61
MIDDLE RECYCLE GAS, KG: 184.98

GAS ANALYSIS IN MOL %

H2: 7.49
N2: 73.27
O2: 0.59
CO2: 9.65
CO: 2.85
CH4: 1.40
C2: 2.90
C3: 1.390
C4: 0.440

BTU PER SCFM: 152.83

DISTRIBUTION OF ORGANIC CARBON
% OIL 40.46
% SPENT SHALE: 38.61
% GAS: 5.93

% UNACCOUNTED CARBON: 15.00

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 38.24
GAS: 4.87
SPENT SHALE: 21.89

YIELD, % OF F.A: 67.70

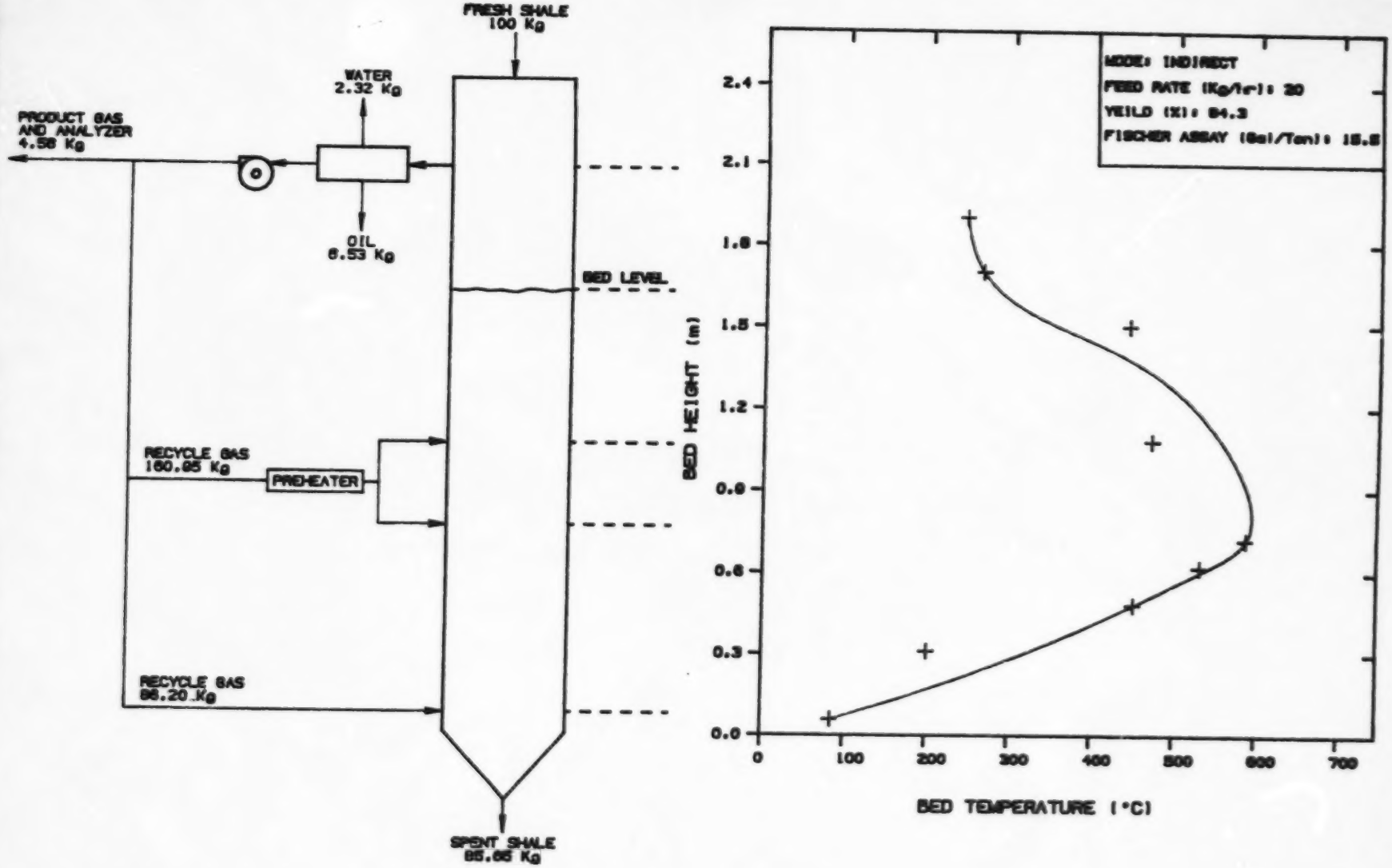


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 35

EXPERIMENT NO:35 SHALE NO: 2

MODE: INDIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.62
FEED RATE, KG/HR: 20.00
DURATION, HR: 13.00
RESIDENCE TIME IN HR: 4.28
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.47
RECYCLE GAS SPLIT, %: BOTTOM: 34.9 MIDDLE: 65.1

INPUT IN KG

FRESH SHALE: 100.00
ACCUM/DEPLE: 0.56
TOTAL INPUT: 100.56

OUTPUT IN KG

SPENT SHALE: 85.65
EXHAUST GAS: 0.
ANALYZER INTAKE: 4.56
OIL PRODUCED: 6.53
WATER FORMED: 2.32
TOTAL OUTPUT: 99.07
% UNACCOUNTED: 1.49

BOTTOM RECYCLE GAS, KG: 86.20
MIDDLE RECYCLE GAS, KG: 160.98

GAS ANALYSIS IN MOL %

H2: 6.58
N2: 75.15
O2: 0.98
CO2: 10.14
CO: 2.15
CH4: 1.17
C2: 2.28
C3: 1.150
C4: 0.400

BTU PER SCFM: 126.35

DISTRIBUTION OF ORGANIC CARBON
% OIL 56.10
% SPENT SHALE: 34.93
% GAS: 4.29

% UNACCOUNTED CARBON: 4.68

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 55.04
GAS: 3.38
SPENT SHALE: 20.90

YIELD, % OF F.A: 84.30

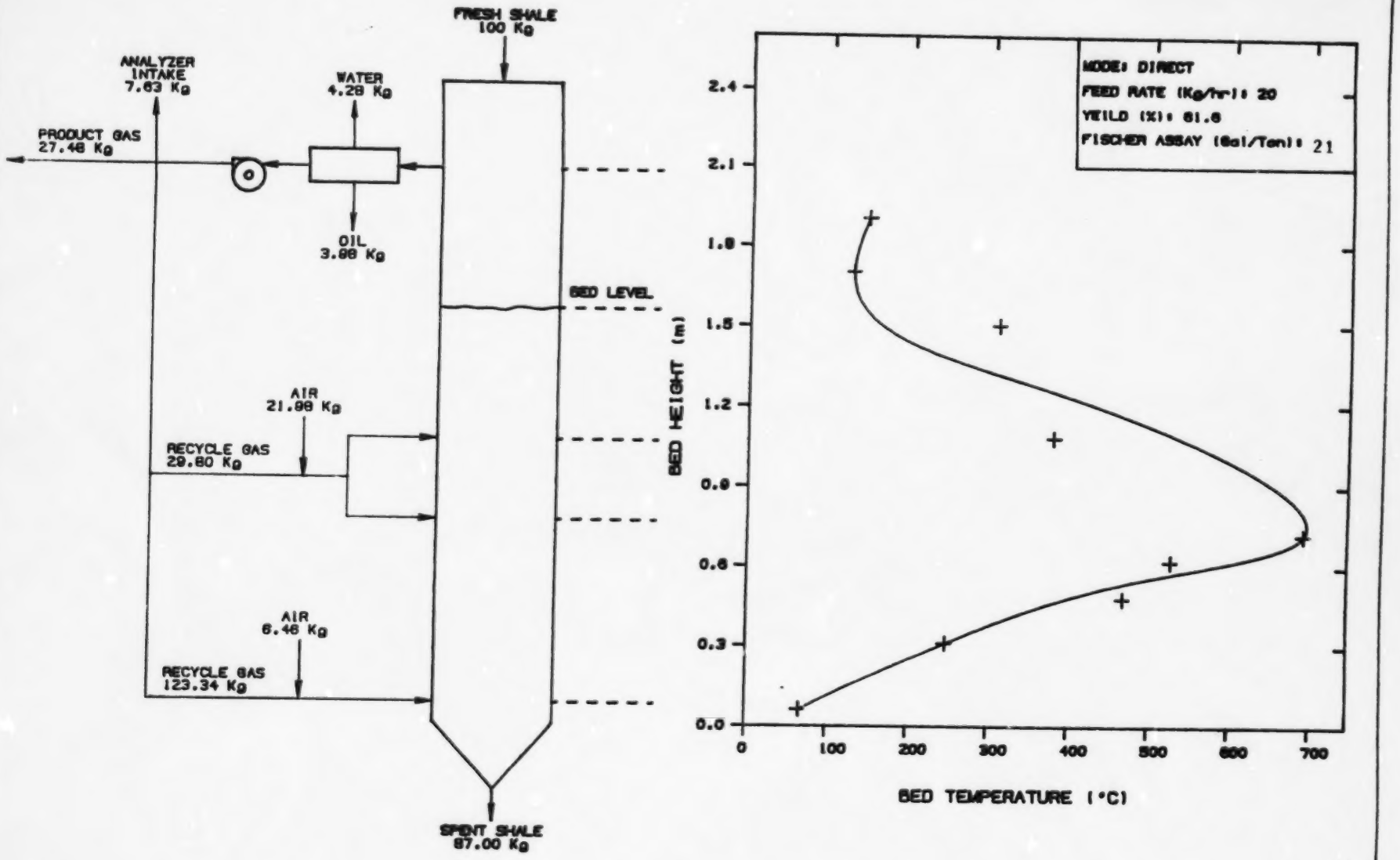


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 36

EXPERIMENT NO:36 SHALE NO: 1

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.55
FEED RATE, KG/HR: 20.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 4.10
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.53
RECYCLE GAS SPLIT, % : BOTTOM: 80.5 MIDDLE: 19.5

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 21.99
AIR BOTTOM: 6.46
ACCUM/DEPLE: -2.43
TOTAL INPUT: 126.01

OUTPUT IN KG

SPENT SHALE: 87.00
EXHAUST GAS: 27.48
ANALYZER INTAKE: 7.63
OIL PRODUCED: 4.28
WATER FORMED: 3.98
TOTAL OUTPUT: 130.37
% UNACCOUNTED: -3.46

BOTTOM RECYCLE GAS, KG: 123.34
MIDDLE RECYCLE GAS, KG: 29.80

GAS ANALYSIS IN MOL %

H2: 1.55
N2: 77.78
O2: 1.61
CO2: 13.10
CO: 1.48
CH4: 1.37
C2: 1.48
C3: 0.950
C4: 0.680

BTU PER SCFM: 99.46

DISTRIBUTION OF CARBON
% OIL 33.05
% SPENT SHALE: 37.31
% GAS: 14.94
% UNACCOUNTED CARBON: 14.69

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 40.20
GAS: 21.40
SPENT SHALE: 24.02

YIELD, % OF F.A: 61.60

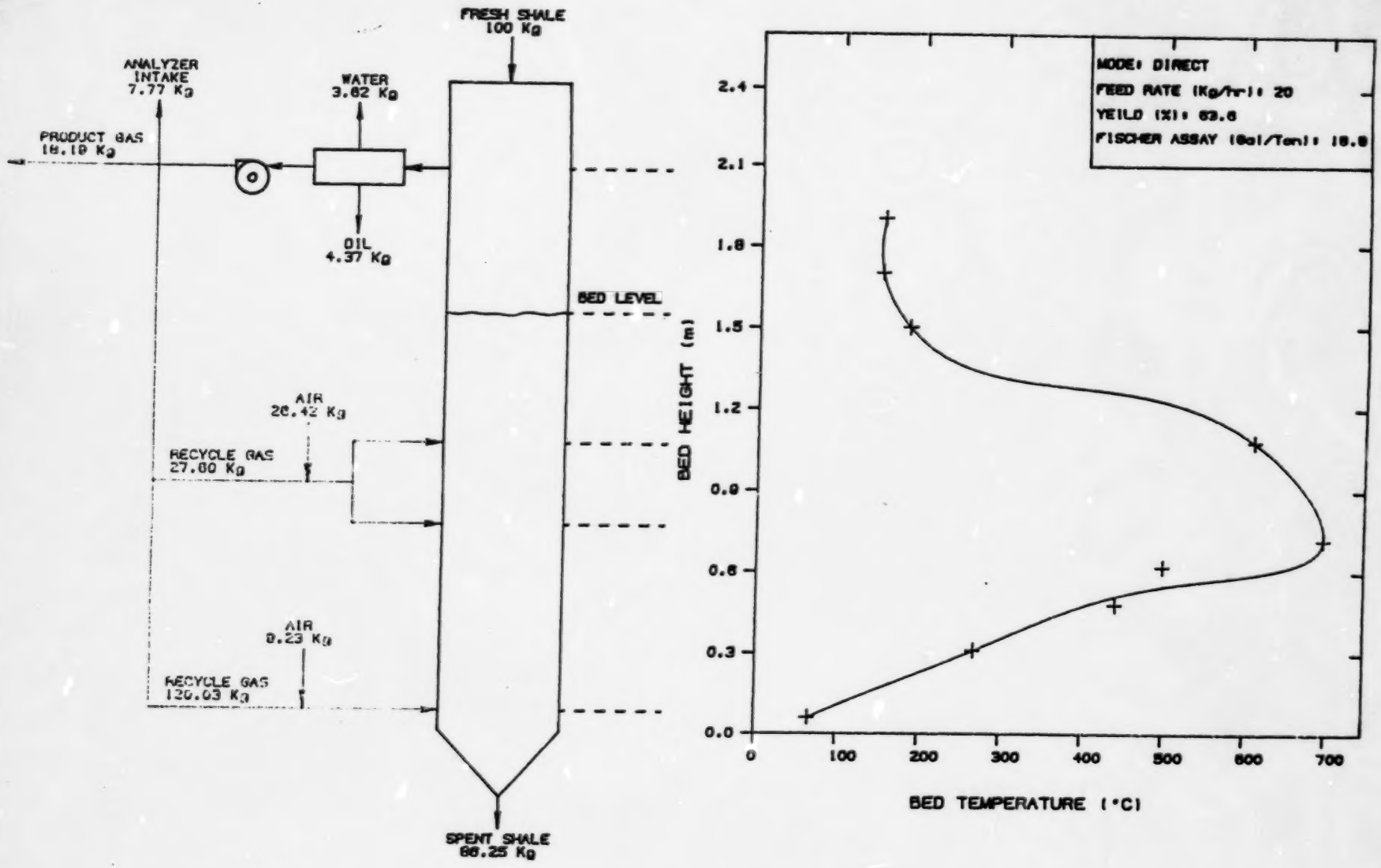


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 37

EXPERIMENT NO:37 SHALE NO: 1

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.52
FEED RATE, KG/HR: 20.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 4.02
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.48
RECYCLE GAS SPLIT, % : BOTTOM: 81.3 MIDDLE: 18.7

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 26.42
AIR BOTTOM: 9.23
ACCUM/DEPLE: 0.61
TOTAL INPUT: 136.25

OUTPUT IN KG

SPENT SHALE: 86.33
EXHAUST GAS: 18.19
ANALYZER INTAKE: 7.77
OIL PRODUCED: 4.37
WATER FORMED: 3.62
TOTAL OUTPUT: 120.28
% UNACCOUNTED: 11.73

BOTTOM RECYCLE GAS, KG: 120.03
MIDDLE RECYCLE GAS, KG: 27.60

GAS ANALYSIS IN MOL %

H2: 2.07
N2: 78.49
O2: 0.30
CO2: 14.10
CO: 1.98
CH4: 1.36
C2: 0.97
C3: 0.440
C4: 0.320

BTU PER SCFM: 67.83

DISTRIBUTION OF CARBON
% OIL 32.74
% SPENT SHALE: 34.93
% GAS: 10.92
% UNACCOUNTED CARBON: 21.41

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 40.18
GAS: 10.84
SPENT SHALE: 24.18

YIELD, % OF F.A: 63.60

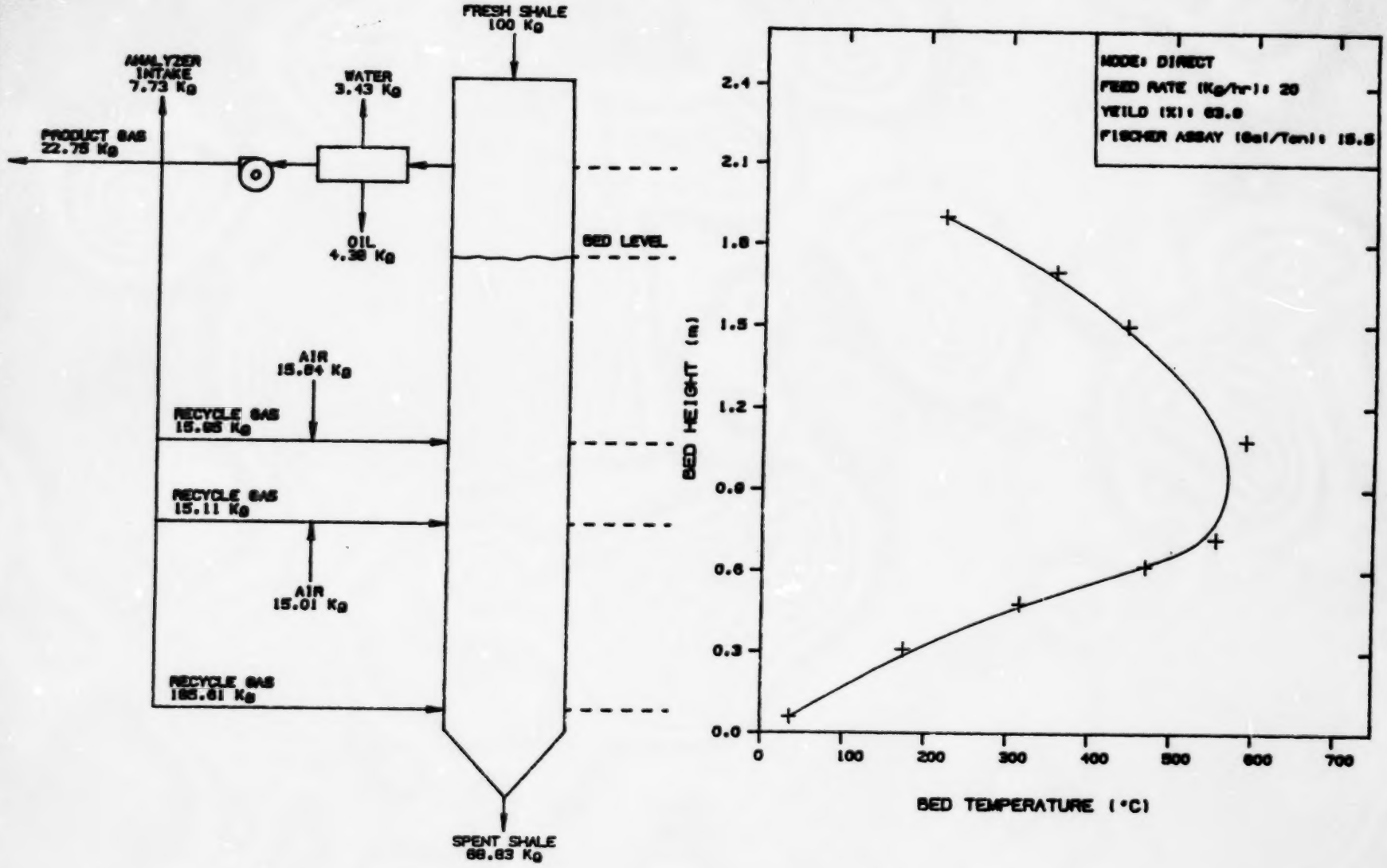


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 41

EXPERIMENT NO:41 SHALE NO: 2

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.74
FEED RATE, KG/HR: 20.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 4.60
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.17
RECYCLE GAS SPLIT, % : BOTTOM: 85.7 MIDDLE: 14.3

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 30.64
AIR BOTTOM: 0.
ACCUM/DEPLE: 2.43
TOTAL INPUT: 133.08

OUTPUT IN KG

SPENT SHALE: 88.83
EXHAUST GAS: 22.75
ANALYZER INTAKE: 7.73
OIL PRODUCED: 4.38
WATER FORMED: 3.43
TOTAL OUTPUT: 127.13
% UNACCOUNTED: 4.47

MID AIR SPLIT
MID AIR UPPER, KG: 15.64
MID AIR LOWER, KG: 15.01

BOTTOM RECYCLE GAS, KG: 185.61
MIDDLE RECYCLE GAS, KG: 31.06

MIDDLE RECYCLE GAS SPLIT, KG
UPPER, KG: 15.95
LOWER, KG: 15.11

GAS ANALYSIS IN MOL %

H2: 2.26
N2: 75.58
O2: 0.
CO2: 17.42
CO: 2.22
CH4: 1.33
C2: 0.73
C3: 0.300
C4: 0.160

BTU PER SCFM: 55.63

DISTRIBUTION OF CARBON
% OIL 36.99
% SPENT SHALE: 36.43
% GAS: 15.84
% UNACCOUNTED CARBON: 10.74

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 46.63
GAS: 11.60
SPENT SHALE: 30.10

YIELD, % OF F.A: 63.90

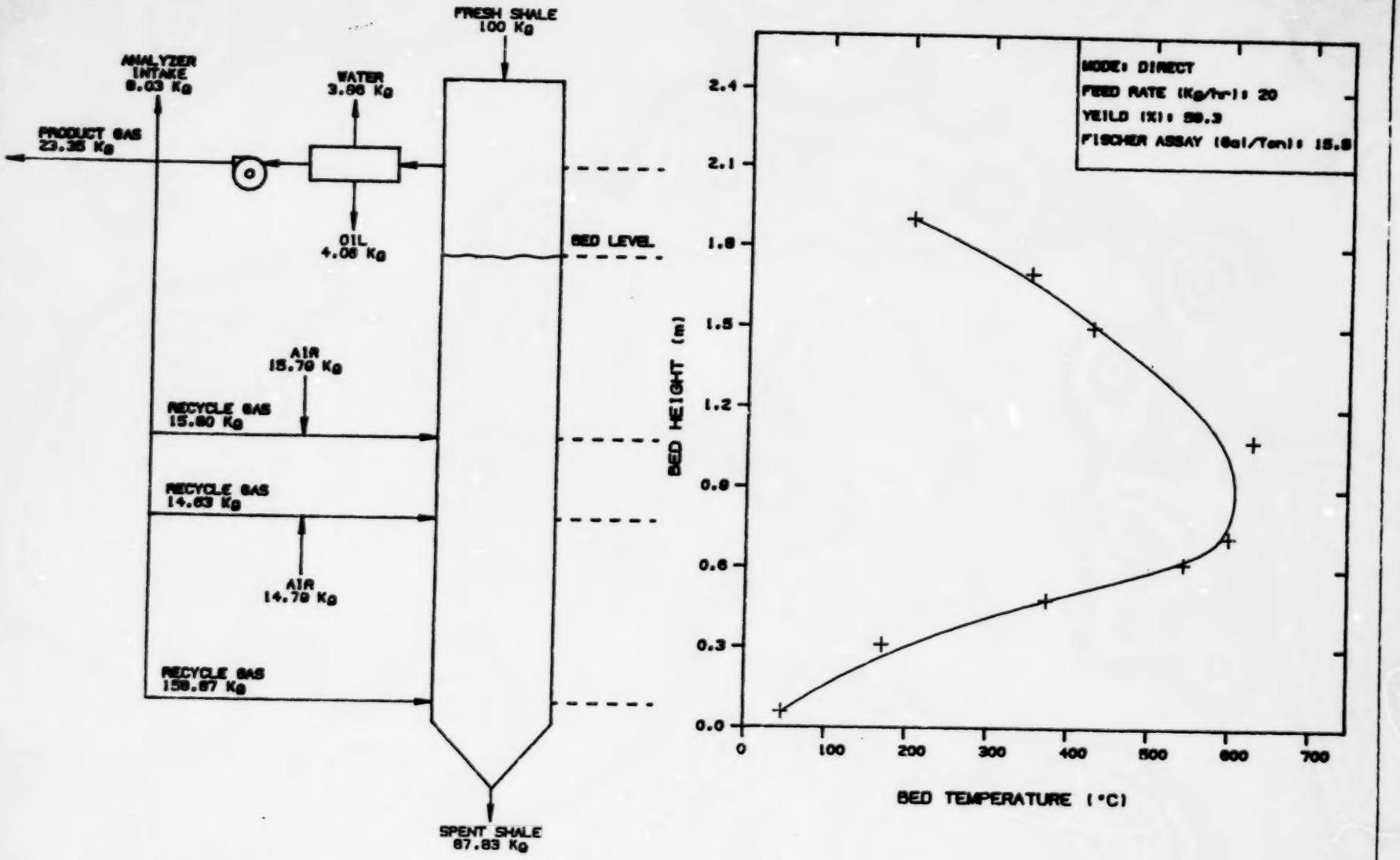


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 42

EXPERIMENT NO:42 SHALE NO: 2

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.74
FEED RATE, KG/HR: 20.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 4.60
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.89
RECYCLE GAS SPLIT, % : BOTTOM: 83.9 MIDDLE: 16.1

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 30.59
AIR BOTTOM: 0.
ACCUM/DEPLE: 0.
TOTAL INPUT: 130.59

OUTPUT IN KG

SPENT SHALE: 87.83
EXHAUST GAS: 23.35
ANALYZER INTAKE: 8.03
OIL PRODUCED: 4.06
WATER FORMED: 3.96
TOTAL OUTPUT: 127.23
% UNACCOUNTED: 2.57

MID AIR SPLIT
MID AIR UPPER, KG: 15.79
MID AIR LOWER, KG: 14.79

BOTTOM RECYCLE GAS, KG: 158.87
MIDDLE RECYCLE GAS, KG: 30.43

MIDDLE RECYCLE GAS SPLIT, KG
UPPER, KG: 15.80
LOWER, KG: 14.63

GAS ANALYSIS IN MOL %

H2: 2.30
N2: 74.67
O2: 0.
CO2: 18.00
CO: 2.50
CH4: 1.38
C2: 0.72
C3: 0.280
C4: 0.150

BTU PER SCFM: 56.20

DISTRIBUTION OF CARBON
% OIL 35.11
% SPENT SHALE: 28.95
% GAS: 17.72
% UNACCOUNTED CARBON: 18.21

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 43.90
GAS: 12.33
SPENT SHALE: 25.32

YIELD, % OF F.A: 59.30

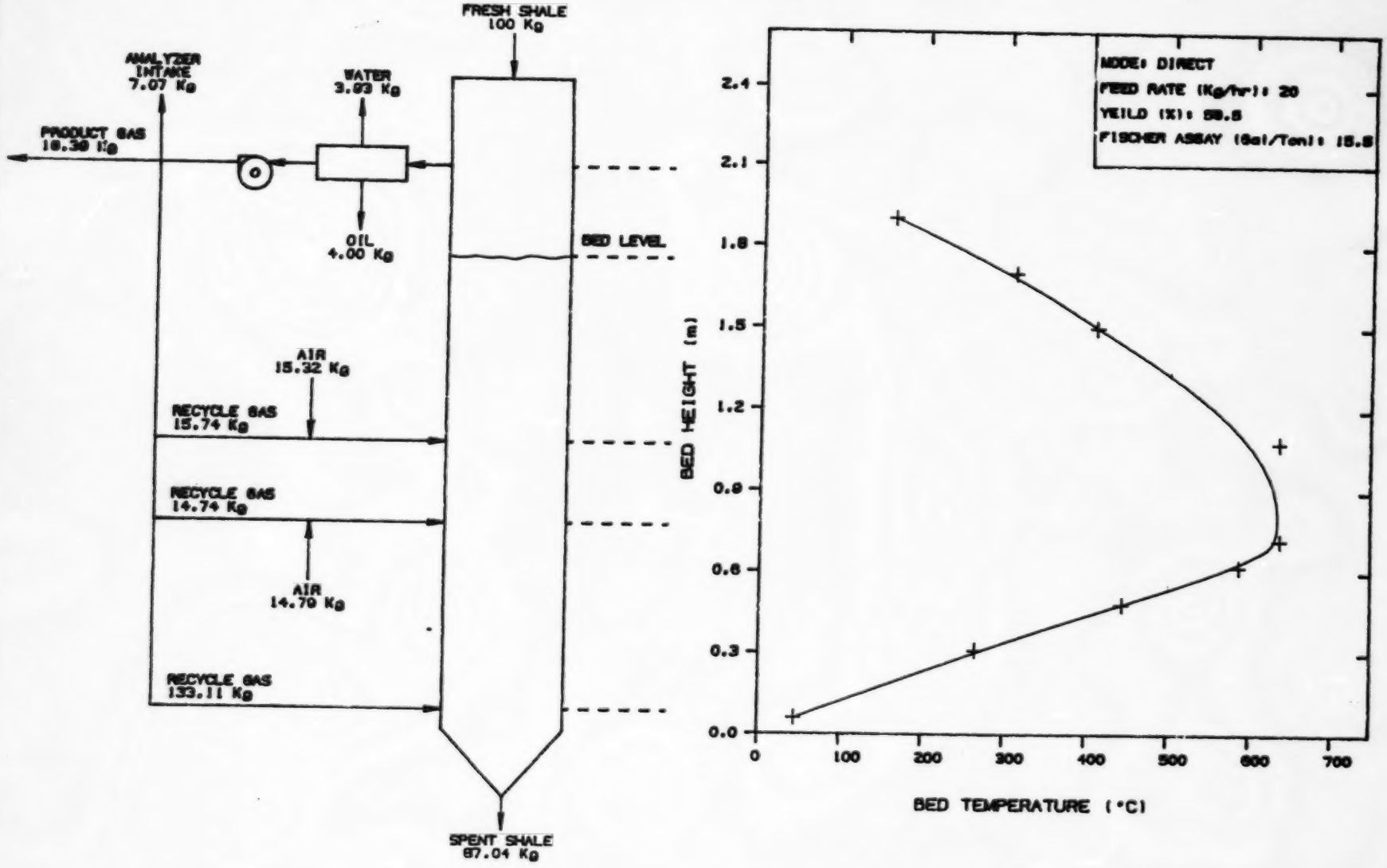


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 43

EXPERIMENT NO:43 SHALE NO: 2

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.74
FEED RATE, KG/HR: 20.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 4.60
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.64
RECYCLE GAS SPLIT, % : BOTTOM: 81.4 MIDDLE: 18.6

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 30.11
AIR BOTTOM: 0.
ACCUM/DEPLE: -1.22
TOTAL INPUT: 128.90

OUTPUT IN KG

SPENT SHALE: 87.04
EXHAUST GAS: 18.39
ANALYZER INTAKE: 7.07
OIL PRODUCED: 4.00
WATER FORMED: 3.93
TOTAL OUTPUT: 120.43
% UNACCOUNTED: 6.57

MID AIR SPLIT
MID AIR UPPER, KG: 15.32
MID AIR LOWER, KG: 14.79

BOTTOM RECYCLE GAS, KG: 133.11
MIDDLE RECYCLE GAS, KG: 30.48

MIDDLE RECYCLE GAS SPLIT, KG
UPPER, KG: 15.74
LOWER, KG: 14.74

GAS ANALYSIS IN MOL %

H2: 2.71
N2: 74.04
O2: 0.
CO2: 17.75
CO: 2.73
CH4: 1.49
C2: 0.80
C3: 0.290
C4: 0.190

BTU PER SCFM: 62.60

DISTRIBUTION OF CARBON
% OIL 35.04
% SPENT SHALE: 32.06
% GAS: 14.83
% UNACCOUNTED CARBON: 18.07

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 44.08
GAS: 11.33
SPENT SHALE: 26.43

YIELD, % OF F.A: 88.80

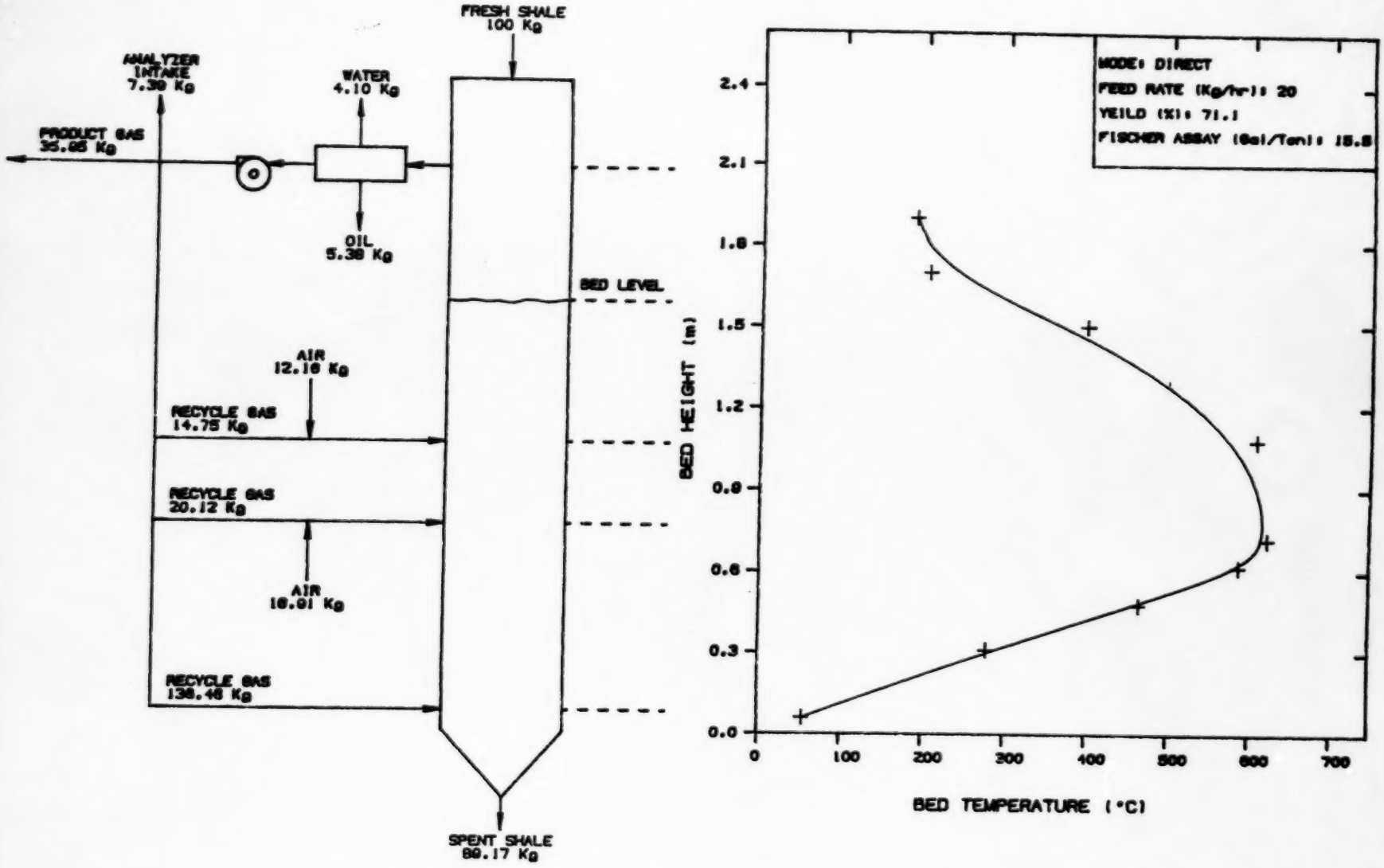


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 44

EXPERIMENT NO:44 SHALE NO: 2

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.58
FEED RATE, KG/HR: 20.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 4.18
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.71
RECYCLE GAS SPLIT, % : BOTTOM: 79.7 MIDDLE: 20.3

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 29.07
AIR BOTTOM: 0.
ACCUM/DEPLE: -0.61
TOTAL INPUT: 128.46

OUTPUT IN KG

SPENT SHALE: 89.17
EXHAUST GAS: 35.95
ANALYZER INTAKE: 7.39
OIL PRODUCED: 5.38
WATER FORMED: 4.10
TOTAL OUTPUT: 141.98
% UNACCOUNTED: -10.52

MID AIR SPLIT
MID AIR UPPER, KG: 12.16
MID AIR LOWER, KG: 16.91

BOTTOM RECYCLE GAS, KG: 136.46
MIDDLE RECYCLE GAS, KG: 34.87

MIDDLE RECYCLE GAS SPLIT, KG
UPPER, KG: 14.75
LOWER, KG: 20.12

GAS ANALYSIS IN MOL %

H2: 2.31
N2: 76.56
O2: 0.51
CO2: 15.86
CO: 2.24
CH4: 1.25
C2: 0.79
C3: 0.310
C4: 0.170

BTU PER SCFM: 56.67

DISTRIBUTION OF CARBON
% OIL 46.74
% SPENT SHALE: 28.85
% GAS: 20.67
% UNACCOUNTED CARBON: 3.74

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 58.97
GAS: 17.45
SPENT SHALE: 25.59

YIELD, % OF F.A: 71.10

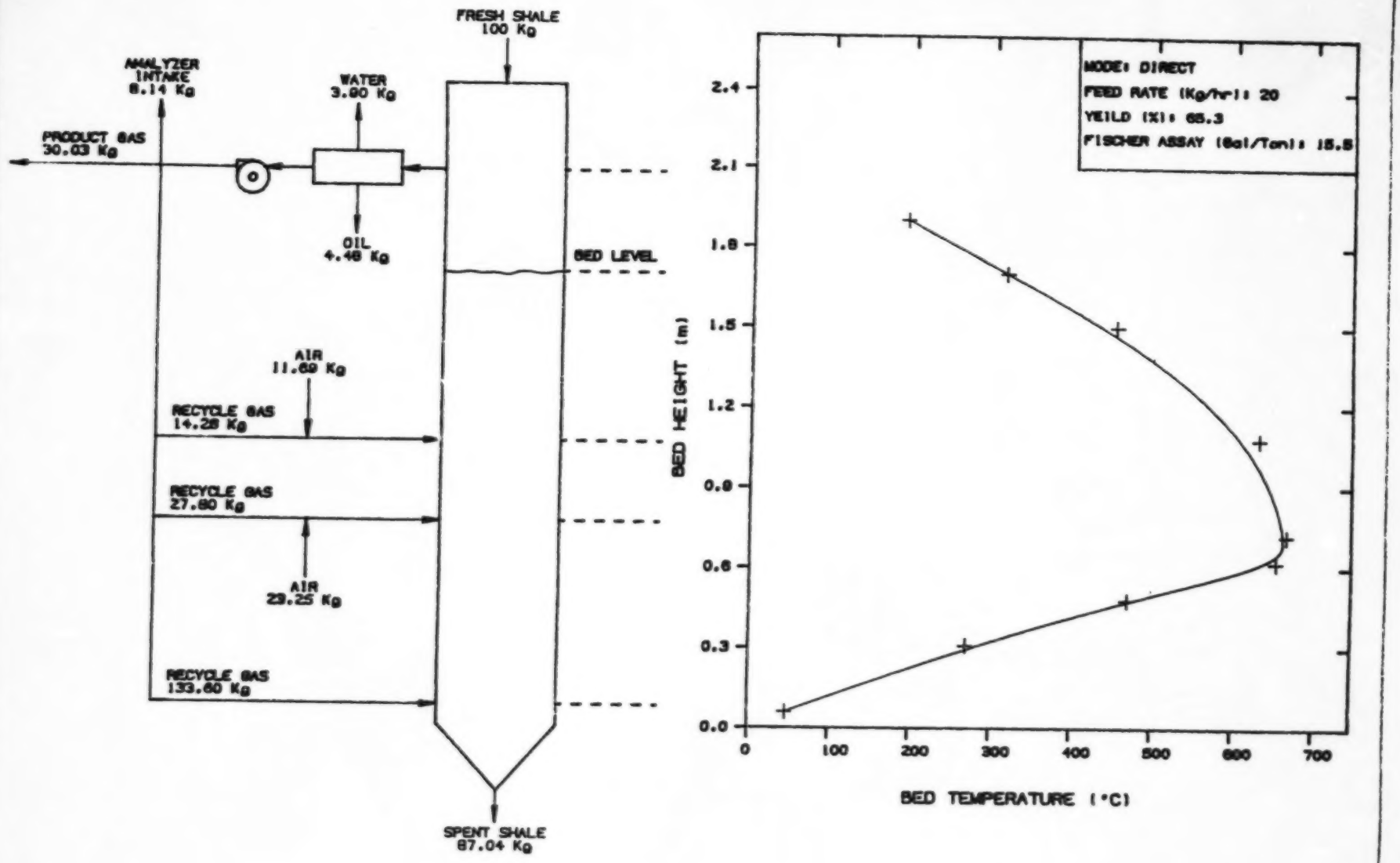


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 45

EXPERIMENT NO:45 SHALE NO: 2

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.69
FEED RATE, KG/HR: 20.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 4.47
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.76
RECYCLE GAS SPLIT, % : BOTTOM: 76.1 MIDDLE: 23.9

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 34.94
AIR BOTTOM: 0.
ACCUM/DEPLE: -0.61
TOTAL INPUT: 134.33

OUTPUT IN KG

SPENT SHALE: 87.04
EXHAUST GAS: 30.03
ANALYZER INTAKE: 8.14
OIL PRODUCED: 4.48
WATER FORMED: 3.90
TOTAL OUTPUT: 133.60
% UNACCOUNTED: 0.54

MID AIR SPLIT
MID AIR UPPER, KG: 11.69
MID AIR LOWER, KG: 23.25

BOTTOM RECYCLE GAS, KG: 133.60
MIDDLE RECYCLE GAS, KG: 42.06

MIDDLE RECYCLE GAS SPLIT, KG
UPPER, KG: 14.26
LOWER, KG: 27.80

GAS ANALYSIS IN MOL %

H2: 2.51
N2: 74.04
O2: 0.
CO2: 18.72
CO: 2.49
CH4: 1.11
C2: 0.69
C3: 0.270
C4: 0.170

BTU PER SCFM: 53.92

DISTRIBUTION OF CARBON
% OIL 38.99
% SPENT SHALE: 29.57
% GAS: 20.37
% UNACCOUNTED CARBON: 11.07

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 49.26
GAS: 14.43
SPENT SHALE: 25.50

YIELD, % OF F.A: 65.30

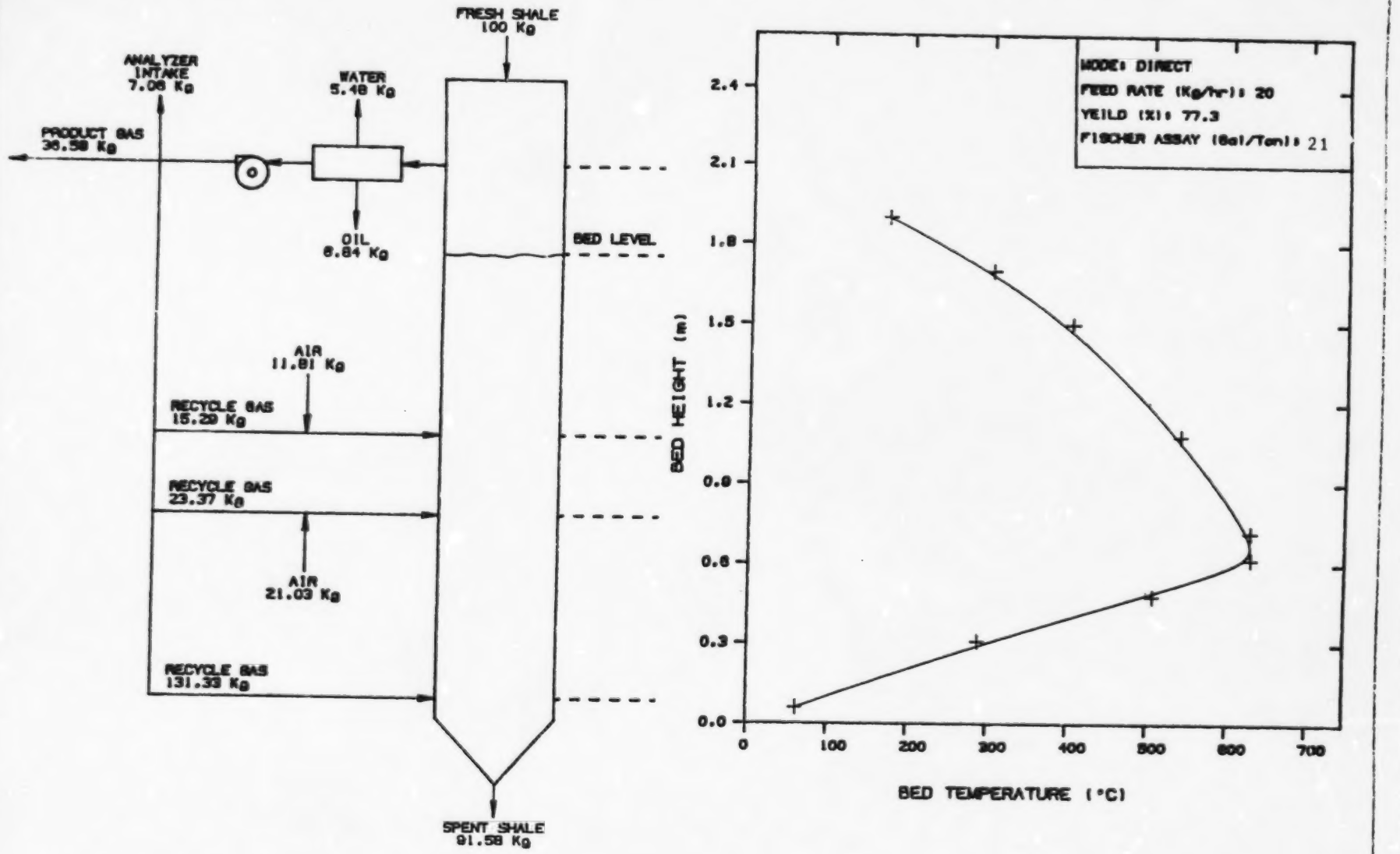


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 46

EXPERIMENT NO:46 SHALE NO: 1

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.74
FEED RATE, KG/HR: 20.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 4.60
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 1.70
RECYCLE GAS SPLIT, % : BOTTOM: 77.3 MIDDLE: 22.7

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 32.84
AIR BOTTOM: 0.
ACCUM/DEPLE: 5.48
TOTAL INPUT: 138.32

OUTPUT IN KG

SPENT SHALE: 91.58
EXHAUST GAS: 36.58
ANALYZER INTAKE: 7.06
OIL PRODUCED: 6.84
WATER FORMED: 5.48
TOTAL OUTPUT: 147.54
% UNACCOUNTED: -6.67

MID AIR SPLIT
MID AIR UPPER, KG: 11.81
MID AIR LOWER, KG: 21.03

BOTTOM RECYCLE GAS, KG: 131.33
MIDDLE RECYCLE GAS, KG: 38.66

MIDDLE RECYCLE GAS SPLIT, KG
UPPER, KG: 15.29
LOWER, KG: 23.37

GAS ANALYSIS IN MOL %

H2: 1.92
N2: 77.88
O2: 0.51
CO2: 15.60
CO: 2.13
CH4: 0.78
C2: 0.61
C3: 0.300
C4: 0.270

BTU PER SCFM: 50.04

DISTRIBUTION OF CARBON
% OIL 48.93
% SPENT SHALE: 35.04
% GAS: 15.28
% UNACCOUNTED CARBON: 0.75

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 60.07
GAS: 12.33
SPENT SHALE: 22.95

YIELD, % OF F.A: 77.30

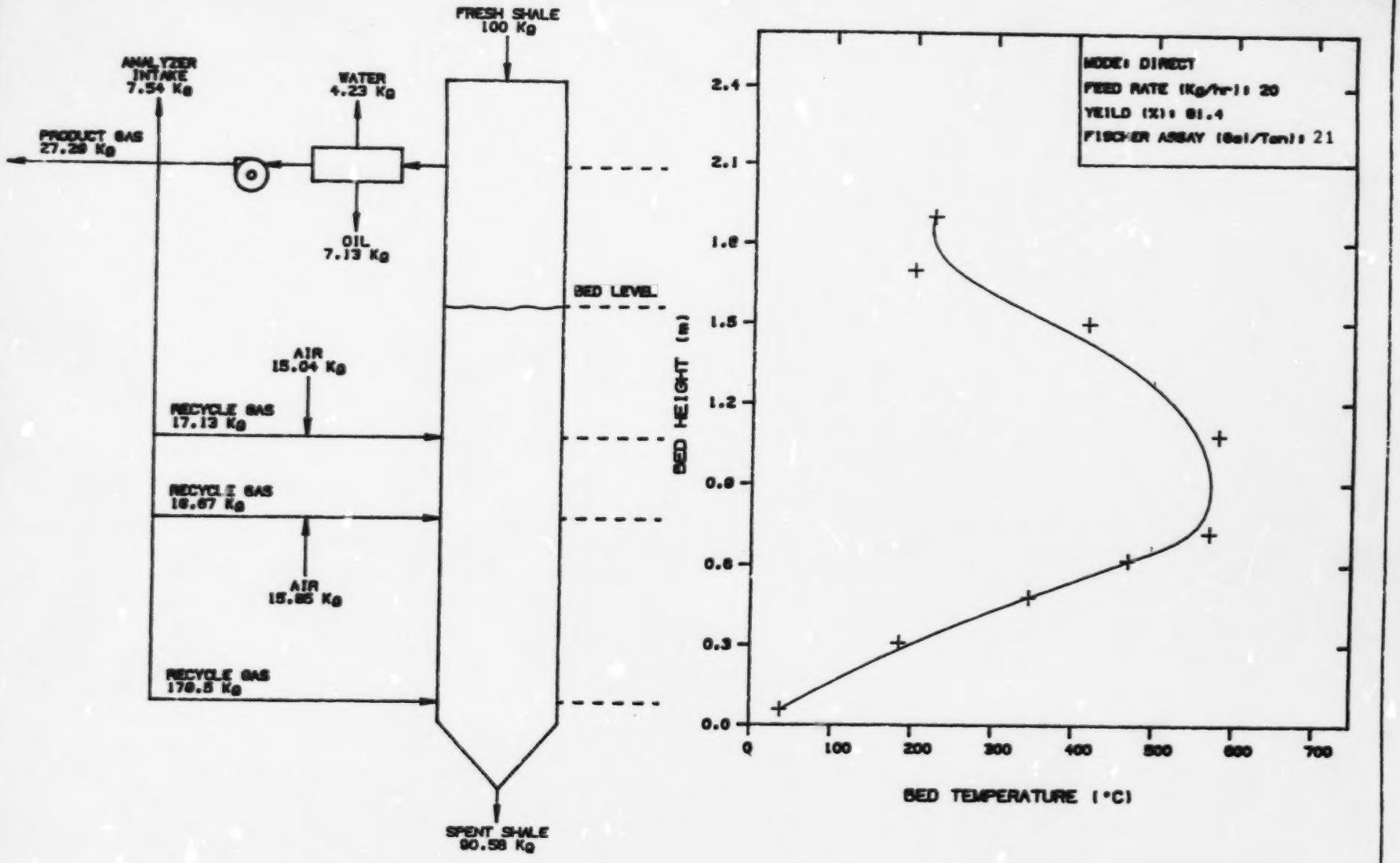


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 47

EXPERIMENT NO:47 SHALE NO: 1

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.55
FEED RATE, KG/HR: 20.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 4.10
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.13
RECYCLE GAS SPLIT, % : BOTTOM: 84.2 MIDDLE: 15.8

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 30.89
AIR BOTTOM: 0.
ACCUM/DEPLE: 3.65
TOTAL INPUT: 134.54

OUTPUT IN KG

SPENT SHALE: 90.58
EXHAUST GAS: 27.29
ANALYZER INTAKE: 7.54
OIL PRODUCED: 7.13
WATER FORMED: 4.23
TOTAL OUTPUT: 136.77
% UNACCOUNTED: -1.66

MID AIR SPLIT
MID AIR UPPER, KG: 15.04
MID AIR LOWER, KG: 15.85

BOTTOM RECYCLE GAS, KG: 179.50
MIDDLE RECYCLE GAS, KG: 33.81

MIDDLE RECYCLE GAS SPLIT, KG
UPPER, KG: 17.13
LOWER, KG: 16.67

GAS ANALYSIS IN MOL %

H2: 1.80
N2: 78.12
O2: 0.10
CO2: 15.70
CO: 2.07
CH4: 1.00
C2: 0.70
C3: 0.310
C4: 0.200

BTU PER SCFM: 51.17

DISTRIBUTION OF CARBON
% OIL 51.89
% SPENT SHALE: 27.52
% GAS: 13.94
% UNACCOUNTED CARBON: 6.65

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 64.39
GAS: 10.25
SPENT SHALE: 21.01

YIELD, % OF F.A: 81.40

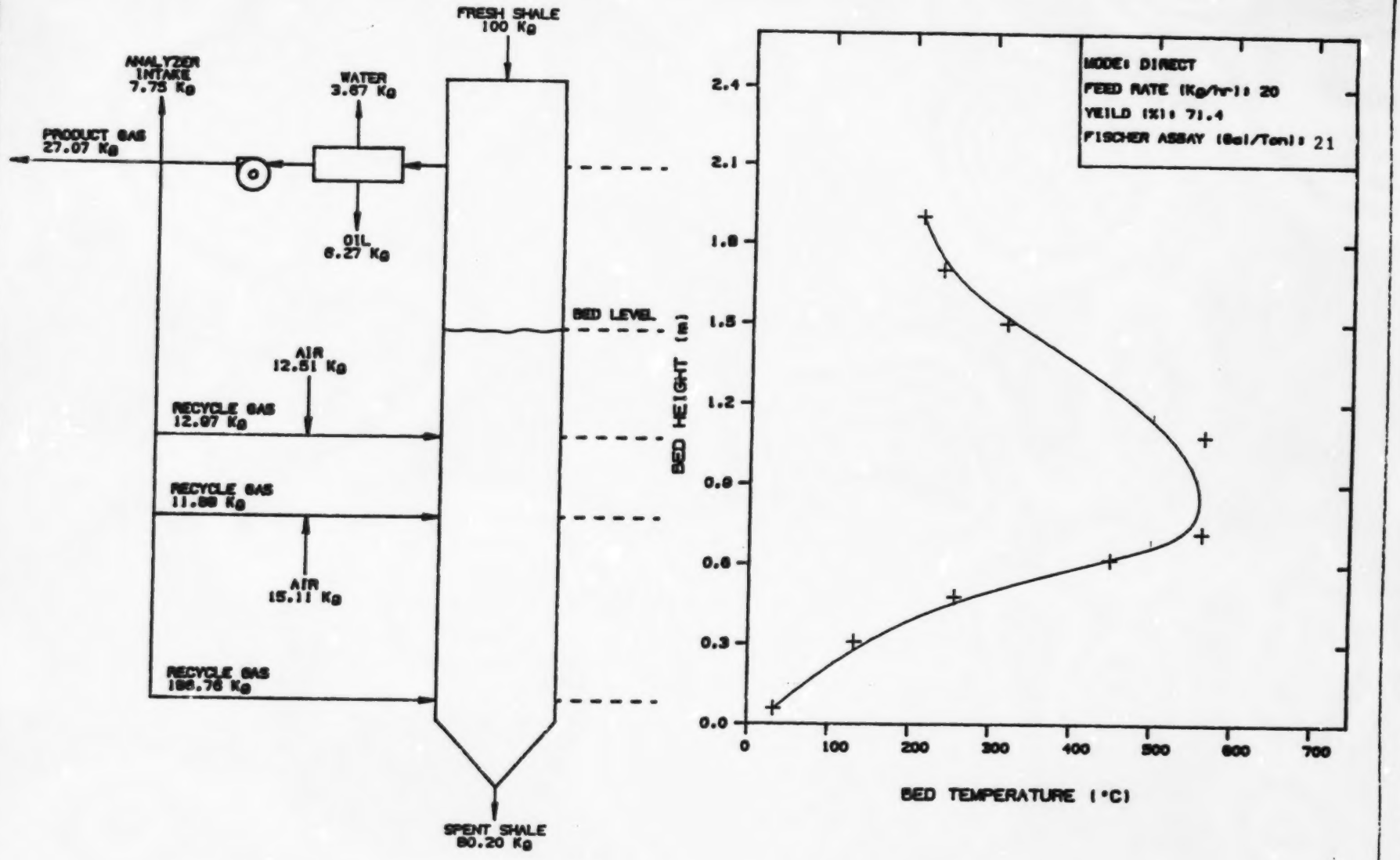


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 48

EXPERIMENT NO:48 SHALE NO: 1

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.46
FEED RATE, KG/HR: 20.00
DURATION, HR: 10.00
RESIDENCE TIME IN HR: 3.86
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.12
RECYCLE GAS SPLIT, % : BOTTOM: 88.3 MIDDLE: 11.7

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 27.62
AIR BOTTOM: 0.
ACCUM/DEPLE: 4.38
TOTAL INPUT: 132.00

OUTPUT IN KG

SPENT SHALE: 80.20
EXHAUST GAS: 27.07
ANALYZER INTAKE: 7.75
OIL PRODUCED: 6.27
WATER FORMED: 3.67
TOTAL OUTPUT: 124.96
% UNACCOUNTED: 5.33

MID AIR SPLIT
MID AIR UPPER, KG: 12.51
MID AIR LOWER, KG: 15.11

BOTTOM RECYCLE GAS, KG: 186.76
MIDDLE RECYCLE GAS, KG: 24.86

MIDDLE RECYCLE GAS SPLIT, KG
UPPER, KG: 12.97
LOWER, KG: 11.88

GAS ANALYSIS IN MOL %

H2: 2.00
N2: 78.96
O2: 0.34
CO2: 14.20
CO: 1.97
CH4: 1.10
C2: 0.73
C3: 0.400
C4: 0.300

BTU PER SCFM: 58.96

DISTRIBUTION OF CARBON
% OIL 45.35
% SPENT SHALE: 33.36
% GAS: 14.36
% UNACCOUNTED CARBON: 6.93

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 56.28
GAS: 11.82
SPENT SHALE: 21.08

YIELD, % OF F.A: 71.40

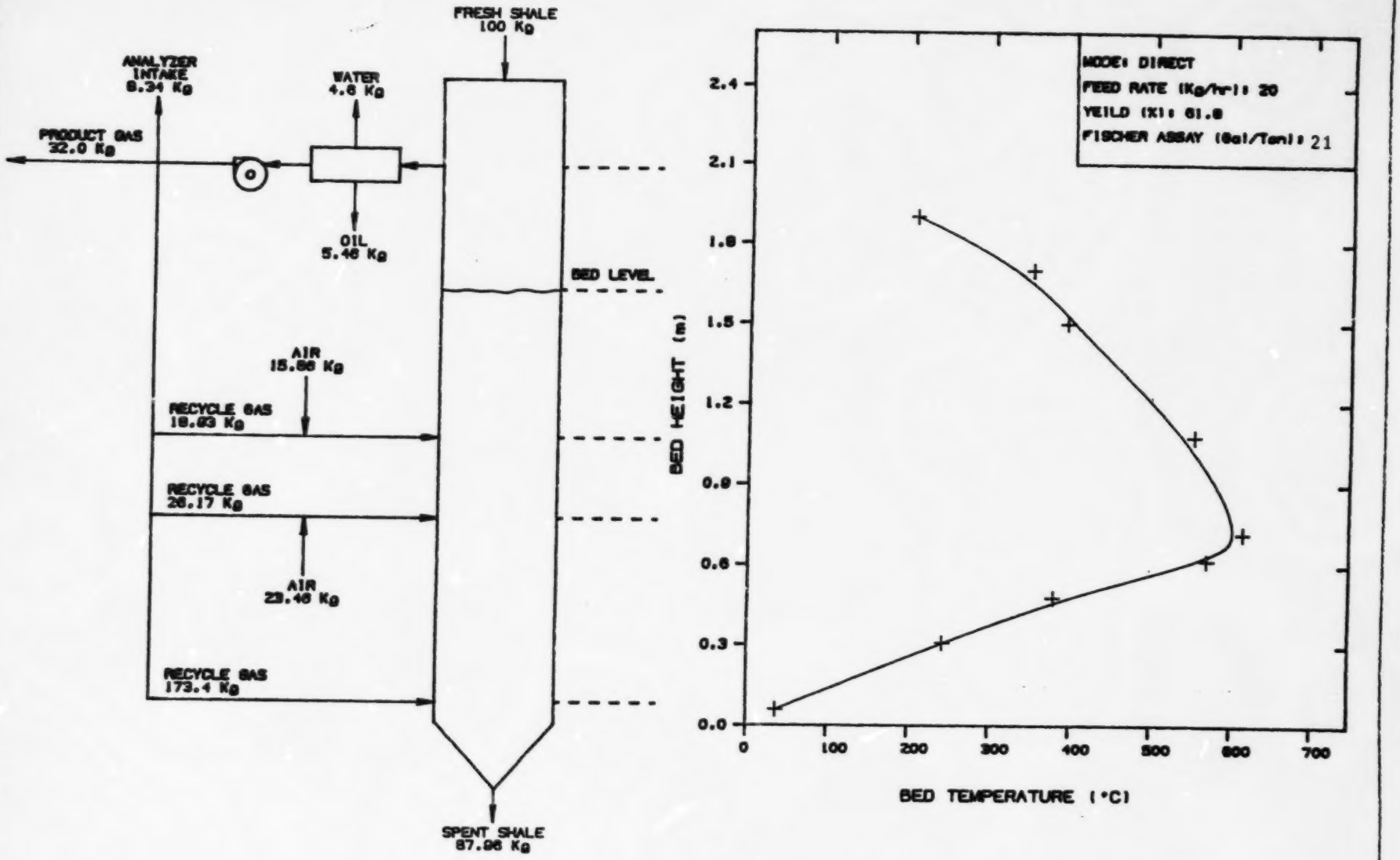


FIG : OPERATING CONDITIONS AND TEMPERATURE PROFILE FOR RUN NO. 49

EXPERIMENT NO:49 SHALE NO: 1

MODE: DIRECT

OPERATING CONDITIONS

BED HEIGHT IN M: 1.61
FEED RATE, KG/HR: 20.00
DURATION, HR: 12.00
RESIDENCE TIME IN HR: 4.26
RATIO OF RECYCLE GAS TO SHALE, KG/KG: 2.18
RECYCLE GAS SPLIT, % : BOTTOM: 79.4 MIDDLE: 20.6

INPUT IN KG

FRESH SHALE: 100.00
AIR MIDDLE: 39.32
AIR BOTTOM: 0.
ACCUM/DEPLE: 2.43
TOTAL INPUT: 141.75

OUTPUT IN KG

SPENT SHALE: 87.96
EXHAUST GAS: 31.99
ANALYZER INTAKE: 8.34
OIL PRODUCED: 5.46
WATER FORMED: 4.60
TOTAL OUTPUT: 138.35
% UNACCOUNTED: 2.40

MID AIR SPLIT
MID AIR UPPER, KG: 15.86
MID AIR LOWER, KG: 23.46

BOTTOM RECYCLE GAS, KG: 173.39
MIDDLE RECYCLE GAS, KG: 45.11

MIDDLE RECYCLE GAS SPLIT, KG
UPPER, KG: 18.93
LOWER, KG: 26.17

GAS ANALYSIS IN MOL %

H2: 1.90
N2: 76.48
O2: 0.22
CO2: 16.40
CO: 2.40
CH4: 1.15
C2: 0.70
C3: 0.350
C4: 0.400

BTU PER SCFM: 62.23

DISTRIBUTION OF CARBON
% OIL 40.20
% SPENT SHALE: 28.02
% GAS: 17.71
% UNACCOUNTED CARBON: 14.07

ENERGY DISTRIBUTION, % OF FRESH SHALE

OIL: 50.05
GAS: 14.54
SPENT SHALE: 25.27

YIELD, % OF F.A: 61.80